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FINAL PROJECT REPORT**

**BUILDING AIR-TIGHTNESS THROUGH
APPLIANCE VENTING STANDARDS**

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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ABSTRACT

Air sealing homes to reduce the uncontrolled entry of outdoor air is one of the most cost-effective home retrofit measures to reduce energy consumption and associated greenhouse gas emissions. However, tighter homes more readily depressurize when exhaust ventilation equipment is operated, making combustion appliances (stoves, water heaters, etc.) more prone to backdrafting and spilling harmful exhaust gases into the living space. This project sought to improve energy efficiency while maintaining occupant health and safety by reducing the combustion appliance barrier to increased air tightening.

In particular, this project used literature review, field measurements, and computer simulations to show that existing “worst case” diagnostic tests are not always accurate in measuring carbon monoxide emissions from combustion appliances. It is more important to identify when the air flow is interrupted in the exhaust vents. There is also a need to assess the indoor air pollutant concentrations and health risks associated with these events.

To reduce or eliminate health and safety risks associated with spillage and the need for testing, the report first recommends using sealed combustion appliances, or moving them outside the occupied space, as one solution. For retrofits, one must instead use a diagnostic procedure to assess the risks of spillage for the house and appliances as found and as they might operate if the house were to be air-tightened. To that end, the report recommendations include: (1) working with industry to reduce the amount of carbon monoxide that new appliances might produce, (2) inspecting all combustion appliance and kitchen ventilation device installations in a house to determine whether they are code-compliant, (3) developing a test procedure that identifies hazardous combinations of appliances and building characteristics, and (4) replacing current diagnostic tests with new tests using challenging conditions that occur more frequently.

Keywords: Residential, ventilation, airtightness, indoor air quality, safety, combustion, appliance, venting, backdrafting, spillage, testing, simulation, standards

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EXECUTIVE SUMMARY

Introduction

Air-sealing of homes by reducing air leakage to decrease the uncontrolled entry of outdoor air is one of the most cost-effective home retrofit measures to reduce energy consumption and associated greenhouse gas emissions. However, tighter homes more readily depressurize when exhaust fan equipment is operated, making combustion appliances such as stoves, water heaters, and furnaces more prone to backdraft and to spill or spread harmful exhaust gases into the living space. Backdrafting and spillage result from a combination of factors that include appliance characteristics and location; vent materials, design, and configuration; airtightness of the house in general and the combustion appliance zone in particular; weather conditions; and use patterns of the appliance and other mechanical systems.

Many tests and other assessment protocols have been developed to identify appliances and houses that present a backdrafting hazard. The two most common test methods for assessing combustion safety are short-term (stress) tests and monitoring. Stress tests, performed under induced conditions, indicate the possibility of backdrafting and capture the effects of outdoor temperature and wind on venting potential only at the time of the test. Monitoring seeks to capture a larger sample by assessing operation under actual conditions over a longer period. However, both test methods may produce misleading results: failing houses when backdrafting are not actually problematic, or passing houses may have problems under some operational conditions.

Since backdrafting and spillage occur only under specific conditions, it is relevant to consider these hazards as having statistical as well as physical characteristics. Surprisingly, however, there is no clearly stated means to identify existing combustion safety test protocols. Specifying a clear risk mitigation objective is important when trying to assess whether an appliance and venting configuration is problematic, and especially to assess whether a test is effective at finding problematic installations.

Goal

This project sought to maintain or improve occupant health and safety while improving energy efficiency by reducing the barriers associated with increased air tightening.

Methods

The project team's approach to overcoming some of the limitations associated with stress tests and monitoring was to use physics-based computer models to simulate the operation of an appliance and other exhaust systems over a typical location-specific weather. In practice, many of the relevant physical parameters, such as wind and temperature are problematic; that is, they vary over time or from house to house. With all of this information and a model that appropriately captures the effects of wind and temperature on exhaust fan use, one can calculate the probable maximum depressurization that would be expected and then predict the occurrence and frequency of sustained backdrafts and spillage and the associated indoor

pollutant concentrations. This information can help identify events that prevent combustion appliances from venting properly.

To that end, the project team first reviewed literature to summarize the metrics and diagnostics used to assess combustion safety, document the technical basis, and investigate the ability to identify risk mitigations.

Next, the project team tested the accuracy of the computer program VENT-II, which simulates exhaust draft thermal performance, including the airflow and pressure dynamics associated with heating the vent. This program has been used to generate vent sizing tables in the National Fuel Gas Code, the model code that provides the minimum safety requirements for design and installation of fuel gas piping systems in homes and buildings. This effort was to assess the ability of VENT-II to predict combustion gas spillage events due to house depressurization by comparing VENT-II simulated results with experimental data for four appliance configurations.

Finally, the project team performed three related simulation studies, which were designed to better understand the risk associated with house depressurization and combustion spillage and to provide a solid knowledge base for future development of improved diagnostics. These studies, which are included as appendices, are broken down into the following:

- The *spillage* study was designed to frame the problem in realistic conditions. It shows the *time evolution of indoor concentrations* when a combustion appliance is spilling under a *constant* house depressurization, using realistic values for the house size, air tightness, emission rate, and emission duration. This study did not, however, specify the *cause* of the depressurization.
- The *airflow driver* study was designed to *relate depressurization to airflows*. It examines, under *steady-state* (or *unchanging*) conditions, how wind, indoor-outdoor temperature differences, and mechanical ventilation combine to establish the pressures and flows that determine backdrafting. This study identified the key parameters that affect *vent flow reversal*, but did not examine the resulting indoor concentrations.
- The *yearly distribution* study was designed to combine the airflow and concentration models **under realistic weather conditions**. It drives an indoor concentration model using observed yearly weather data from 16 California climate zones. This puts the results of the other two simulation studies into context by accounting for the actual distributions of the wind and temperature conditions that help set airflow.

Results

The project team's literature review found that the objectives of available test methods, both stress and monitoring, are not clearly defined. Implicitly, the tests apply separate and conflicting criterion, with any occurrence of backdrafting or spillage regarded as a failing condition. The following are three of the most important other key findings and gaps in the literature that the team reviewed:

- Venting systems that meet the requirements of the National Fuel Gas Code are more likely to vent properly.

- Carbon monoxide output under downdraft conditions can be reduced if combustion appliances are properly cleaned and tuned.
- Due to their construction, gas water heaters with standard updraft flues have a greater backdrafting potential than furnaces. However, available data indicate that conventional storage water heaters very rarely have high carbon monoxide emissions.

In terms of the project team's effort to validate VENT-II, two of the most important findings were that:

- VENT-II correctly predicted spillage for appliances operating in cold and mild outdoor conditions but could not accurately predict spillage for hot outdoor conditions.
- Due to inconsistent errors within the software, exact spillage could not be determined for a few cases. Therefore, VENT-II may not properly identify appliances that are spilling in practice.

Although VENT-II provides a first step towards modeling vent systems, further development is still required to produce a reliable program that can correctly predict spillage caused by depressurization. From this study, the project team recommended that the VENT-II solver be investigated further and more detailed instructions be provided when modeling single-appliance vent systems.

The project team's subsequent simulations using a simple box model (simplified simulation of a complex system) and then a more elaborate and complete multizone airflow-pressure-contaminant transport analysis program (CONTAM) showed that current diagnostics tests are not nearly as useful as people think for finding problems. Broadly speaking, the simulations suggest that current limits on fan-induced pressure change should be considered only rules-of-thumb that probably lead to overly cautious air tightening and remediation and do not necessarily represent worst cases that occur at modest rather than maximum depressurization. In summary, some of the most important other findings of the team's simulations are:

- For short (5 minutes or less) emission spills, current combustion safety protocols are protective against life-threatening carbon monoxide conditions, even when the appliance is malfunctioning and has repeated intermittent spillage. However, the protocols likely establish carbon monoxide thresholds that are too conservative for *large* houses with infrequent spillage events.
- Prolonged or continuous spillage events in a *moderately* airtight house could produce an acute hazard if the burner is malfunctioning. Therefore, combustion safety protocols should ensure that conditions of sustained spillage and high emissions do not exist without high ventilation.
- Reaching life-threatening conditions in a *moderately* tight house with a natural draft appliance is rare and almost impossible for an induced draft appliance. However, in a *very* tight house (2 air changes per hour at 50 Pascals or tighter), the combination of low air change rate and increased risk of spillage significantly increases the potential for prolonged pollutant exposure that could lead to a safety hazard.

- The most dangerous conditions result from *stalled flow* in the appliance vent shaft. However, while strong depressurization and negative (inward) airflows bring combustion products into the occupied space, these airflows also *dilute* the combustion products. This important phenomenon has not been recognized until now.
- Fan-induced pressure change—the metric used in current stress testing—does not directly assess whether flow will stall or reverse in the vent shaft. The pressure change needed to reverse flow in the vent shaft depends not only on fan-induced pressure differences, but also on naturally-induced weather-related pressure differences, which vary throughout the year.
- A large enough fan-induced pressure change does imply backdrafting. However, by the time fan-induced pressure change is large enough to guarantee backdrafting, it is almost never a concern with indoor air quality, due to the dilution effect of outdoor air entering through the vent.
- Regardless of fan-induced depressurization, a building professional should always ensure that the appliance burner is clean, the appliance is functioning properly, the vent system is connected to the appliance, and draft is established in a short period of time.

In the end, using sealed combustion appliances or locating them outside the occupied space is one solution to reducing or eliminating health and safety risks associated with spillage. However, especially in retrofit situations, doing so may not be cost effective. In these cases, a diagnostic procedure should be used to assess the risks of spillage for the house and appliances as found and also how they may operate if retrofits (such as house air tightening) are implemented. This report outlines a series of seven recommended changes to current combustion safety diagnostics based on the findings of the project team’s literature review and simulation studies. These include:

1. Eliminate comparisons of worst-case depressurization test results to threshold limits by appliance type.
2. Ensure that diagnostic protocols include inspections of air supply, appliance operation, and venting.
3. Include a draft test under challenging (but not worst case) depressurization conditions.
4. Apply assurance procedures to all appliances used as heat sources in the house.
5. Include kitchen ventilation in combustion safety assessments.
6. Coordinate with the American National Standards Institute (ANSI) to reduce allowable carbon monoxide levels in new appliances.
7. Develop a condition assessment / calculation procedure that considers burner size, dilution volume, and air change rate.

Details about these recommendations are contained within the body of this report. With respect to the last recommendation, simulations similar to those reported here could be used as part of

a future screening tool, either to help translate field measurements into a risk assessment, or to guide the field tests toward an appropriate level of testing.

Conclusions

Air sealing of homes to reduce the uncontrolled entry of outdoor air is typically among the most cost-effective home retrofit measures to reduce energy consumption and associated greenhouse gas emissions. However, tighter homes more readily depressurize when exhaust ventilation equipment is operated, making combustion appliances more prone to backdraft and spill harmful exhaust gases into the living space. The goal of this project was to improve energy efficiency while maintaining occupant health and safety by reducing the combustion appliance barrier to increased air tightening. In particular, this project used a literature review, field measurements, and computer simulations to show that existing “worst case depressurization” based diagnostic tests are fundamentally flawed, that a more important consideration is identifying when flows stall in combustion appliance vents, and there is a need to assess the statistical variation of spilled pollutant concentrations and associated health risks.

The report recommends using sealed combustion appliances or locating them outside the occupied space as a solution to reducing or eliminating the health and safety risks associated with spillage and the need for testing. Additionally, the report also recommends using a diagnostic procedure instead of assessing the risks of spillage for the house, and appliances within the house, in retrofit situations, particularly where doing so may not be cost effective. This also applies to how appliances might operate if the air envelope of the house were further tightened beyond the pre-existing level. The report also provides further recommendations, such as: (1) working with industry to reduce the amount of carbon monoxide produced by new appliances, (2) inspecting all combustion appliances and kitchen ventilation installations in a house to determine code compliance, (3) developing a condition assessment procedure that identifies hazardous combinations of appliances and building characteristics, and (4) replacing current diagnostic tests with draft tests that occur more frequently under challenging conditions.

Project Benefits

The project team identified several benefits that result directly from this study or that will accrue over time as necessary information and infrastructure develops further. The most important benefit of this project is the new knowledge about risk-based approaches to combustion appliance diagnostics for protecting health and safety, all of which could ultimately be used to update California’s Energy Code (Title 24, Part 6). In particular, this task identified risk based metrics (e.g., vent flow stall rather than worst case depressurization) for better characterizing the circumstances necessary for safe operation of combustion appliances in houses. To that end, this task shows that worst case depressurization is the wrong metric, and shows that depressurization beyond that which corresponds to vent flow stall actually reduces indoor pollutant concentrations by providing dilution airflow through the vent.

This project resulted in six key instances of public dissemination of this new knowledge. Three are formal reports or papers that have been included as appendices within this report. Another

three involve industry-facing presentations and articles. These reports, presentations, and articles indirectly benefit ratepayers by furthering the research on this topic and potentially leading to greatly increased ventilation test standards that will improve health and safety. This research is important since the air envelopes of new homes will become tighter in the future.

CHAPTER 1:

Introduction

1.1 Background

The exhaust from residential combustion appliances, such as furnaces and water heaters, contains air pollutants and high levels of moisture that must be conveyed to the outdoors to maintain acceptable indoor air quality. Exhausting combustion products from the appliance outlet through the vent system to the outdoors, requires a net positive available draft at the appliance outlet (D_a), according to the physical relationship described in Equation 2.1:

$$D_a = D_t - \Delta p - D_p. \quad (2.1)$$

In this equation, D_t is the upward natural draft produced by the buoyancy of hot gases in the vent system relative to air surrounding the vent (theoretical draft), Δp is the sum of pressure losses due to flow resistance in the vent system (i.e., vent inlet, outlet, fittings such as elbows, and friction losses), and D_p is the depressurization of the space surrounding the combustion appliance relative to outdoors where the chimney discharges.¹

Retrofits to increase energy efficiency can interfere with natural draft appliance venting. In particular, air sealing creates tighter buildings that more readily depressurize. Depressurization can vary over time and depends on building envelope and interior partition airtightness, door and window opening, weather-related natural driving forces (wind and indoor-outdoor temperature effects), and on mechanical driving forces (i.e., operation of exhaust fans, clothes dryers, and other combustion appliances). Installation or upgrades of kitchen and bath exhaust fans to meet residential ventilation requirements such as the American Society of Heating, Ventilating and Air Conditioning Engineers (ASHRAE) Standard 62.2² can further depressurize homes, making combustion appliances more prone to backdrafting (when flow is reversed in the chimney during appliance operation) or spillage (combustion product entry into the building).

Currently, two approaches are used to determine if a natural draft appliance inside a home is susceptible to spillage of hazardous combustion gases: (1) monitoring appliance operation and parameters indicating the occurrence of backdrafting or spillage for an extended period, such as one-week, and (2) conducting instantaneous measurements under induced conditions and extrapolating results to predict performance under normal use, also known as short-term or stress tests.

1 ASHRAE. 2012. "Chapter 35: Chimney, Vent, and Fireplace Systems". *ASHRAE Handbook: HVAC Systems and Equipment Volume*. Atlanta, GA: ASHRAE.

2 ASHRAE. 2010. *Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings, ANSI/ASHRAE Standard 62.2*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Monitoring for backdrafting and spillage under normal use conditions typically offers more reliable results and, if carried out over extended periods, inherently measures the performance over a broader range of use and weather conditions relative to stress tests. However, monitoring methods can be expensive due to the cost of equipment, set-up and removal of equipment, and subsequent data analysis. Additionally, long-term data collection is not practical for contractors to be effective and efficient when assessing safety for individual homes.

Stress tests typically seek to induce “worst-case” conditions on a given day by operating all exhaust fans at their highest settings and opening or closing interior doors to achieve the highest level of depressurization in the occupiable area of the house containing the combustion appliance of interest. This area is referred to as the combustion appliance zone (CAZ). Although the stress test methods are less costly and time consuming than monitoring, they can still require hours of effort by trained technicians. Additionally, the stress tests only indicate the possibility of backdrafting and do not address the *frequency* of the factors that contribute to depressurization-induced backdrafting or spillage. These factors include coincident operation of exhaust fans and the appliance, and the effects of weather variations. The stress tests were explicitly developed to assess venting performance during cold-weather venting conditions, making them inappropriate for assessing venting during warm weather conditions, and they are especially susceptible to wind-induced variations of depressurization. As a result, the stress tests sometimes fail: the tests can indicate an appliance is a hazard even though backdrafting is not actually problematic; in other cases, the tests can indicate an appliance is permissible to operate even though the appliance does not robustly vent throughout the range of local weather conditions.

1.2 Goal

The goal of this project, which is entitled “Building Air-Tightness through Appliance Venting Standards”, was to improve energy efficiency while maintaining occupant health and safety by reducing the combustion appliance barrier to increased air tightening.

1.3 Report Structure

This report presents the project team’s findings and recommendations that resulted from investigating the need for improved combustion safety diagnostics in houses. The remainder of this report is structured as follows:

Chapter 2 “**Method**” discusses the subtasks that the team undertook and the approach to the research to accomplish project objectives. In particular, this chapter discusses the original objectives, the purpose of the literature review, the reasons for using simulations and for carrying out a validation of VENT-II, changes to the testing and simulation plans, and the resulting “Spillage, Airflow, and Yearly Distribution Simulation Studies” that were conducted.

Chapter 3 “**Results**” presents the key findings from the team’s investigations, their implications, the need for improved simulation tools, and what is recommended for future activities.

Chapter 4 “**Benefits to California**” describes several benefits stemming from this work, with a focus on the new knowledge that has been created and the dissemination of such to industry.

Following the “**Acronyms and Symbols**”, “**Glossary**”, and “**References**” sections, there are four technical Appendices, as follows:

- “**Appendix A: Assessment of Literature Related to Combustion Appliance Venting Systems**” summarizes the metrics and diagnostics used to assess combustion safety, documents their technical basis, and investigates their risk mitigations. It compiles information from the following: codes for combustion appliance venting and installation; standards and guidelines for combustion safety diagnostics; research evaluating combustion safety diagnostics; research investigating wind effects on building depressurization and venting; and software for simulating vent system performance.
- “**Appendix B: Predicting Backdrafting and Spillage for Natural-Draft Gas Combustion Appliances: Validating VENT-II**” describes the project team’s work to assess VENT-II’s ability to predict combustion gas spillage events caused by house depressurization. In particular, it compares VENT-II simulated results with experimental data that the project team collected for four appliance configurations.
- “**Appendix C: Residential Combustion Gas Spillage: Impacts of Airtightness and Airflows on Indoor Air Pollutant Concentrations**” discusses the three sets of computer simulations that the project team carried out to better understand the *risk* associated with house depressurization and combustion spillage. These simulations involved: a “spillage study” to explore the time evolution of indoor concentrations when a combustion appliance is spilling with constant airflows; an “airflow driver study” to assess which airflow-related parameters under steady-state conditions are most important in establishing the pressures and flows that determine backdrafting; and a “yearly distribution study” that combined the airflow and concentration models under realistic weather conditions to assess the annual statistical variation of pollutant concentrations.
- “**Appendix D: Box Model - Exposure to Intermittent Sources**” shows details behind some of the box model results presented in Section C3 of Appendix C.

CHAPTER 2:

Method

2.1 Original Objectives

The original objectives of this project were predicated on the assumption that current combustion safety diagnostics correctly used house depressurization as an accurate surrogate for safety (i.e., less depressurization means a safer condition), but the diagnostics needed some modifications to increase their reliability to facilitate air tightening by better diagnosing potential combustion safety issues. Broadly, the objectives involved combining measurements and simulations to produce improved test methods, guidelines, and standards. More specifically, the objectives were:

1. Building upon Lawrence Berkeley National Laboratory's (LBNL) Residential Commissioning Literature Review³, determine the current state-of-the-art in combustion appliance backdrafting and spillage tests.
2. Characterize the flow resistance of appliance venting system elements to support the development of new diagnostics that are less sensitive to wind effects and are more repeatable.
3. Use field tests in a sample of California houses to demonstrate the improved repeatability of new diagnostics, and extend the test results over a broad range of conditions using computer simulations and LBNL's airtightness database to determine the potential energy, indoor air quality (IAQ), and environmental benefits of improved airtightness enabled by the new diagnostics.
4. As an extension of related efforts in the California Energy Commission's (Energy Commission) "Residential Energy Savings from Airtightness and Ventilation Excellence" (RESAVE) research project that LBNL was already carrying out, provide guidance on appropriate air tightening practices for the building envelope (and interior partitions) and on related combustion safety diagnostics to California's Energy Code (Title 24, Part 6)⁴ and the American Society for Testing and Materials (ASTM) Committee E6 staff to support incorporation of project findings in these documents.

3 Wray, C.P., M.A. Piette, M.H. Sherman, R.M. Levinson, N.E. Matson, D.A. Driscoll, J.A. McWilliams, T.T. Xu, and W.W. Delp. 2000. "Residential Commissioning: A Review of Related Literature". *Lawrence Berkeley National Laboratory Report, LBNL-44535*.

4 CBSC. 2010a. "California Energy Code: California Code of Regulations, Title 24, Part 6". California Building Standards Commission. Washington, DC: International Code Council.

2.2 Literature Review

In particular, the purpose of the literature review was to summarize the metrics and diagnostics used to assess combustion safety, document their technical basis, and investigate their ability to identify risk mitigations. The review compiled information from the following: relevant codes for combustion appliance venting and installation; standards and guidelines for combustion safety diagnostics; research evaluating performance of the combustion safety diagnostics; research investigating backdrafting and spillage; research investigating wind effects on building depressurization and venting; and software simulating vent system performance.

In summary, as described in more detail in Appendix A, the literature review showed that several measures, such as vent sizing codes and combustion safety diagnostics, have been put in place with the intent to prevent combustion spillage. Research, to an extent, has assessed existing combustion safety diagnostics for depressurization-induced spillage. However, the statistical effects of weather (especially wind) on house depressurization and appliance venting performance are not assessed and the risk mitigation objectives are not clearly defined. Before improved diagnostics can be developed and related targets can be set, additional research is needed to quantify the frequency of test “failure” occurrence throughout the building stock, identify the risk of combustion spillage occurrences, and identify the risk associated with combustion spillage (including health risk from carbon monoxide, oxides of nitrogen, and moisture related problems). Incorporating weather variations, house ventilation system characteristics, and emission spillage rates into existing simulation software may assist such analyses and also with developing more reliable diagnostics for use on-site in California and nationwide. As such, it became clear that the original objectives needed to be modified.

2.3 Simulation Studies Overview

For an individual house, long-term monitoring is the most certain method of determining the distribution of backdrafting and elevated pollutant concentration events (e.g., their frequency, duration, and severity). However, monitoring can be expensive, and requires nontrivial expertise to collect and interpret data. To overcome this barrier, the project team modified the project objectives to instead use simulations to investigate the pollutant concentrations that can occur indoors due to depressurization-induced backdrafting. Simulation studies are useful for identifying conditions that are likely to produce backdrafting, possibly motivating the use of long-term monitoring or other interventions. Such studies can more easily investigate the correlation between weather conditions, house depressurization, combustion spillage, and pollutant exposure. More specifically, the team used the simulations to identify scenarios that could lead to high indoor pollutant concentrations resulting in illness or death. The modified objectives were to provide a scientific basis for identifying the exposure risk associated with backdrafting appliances, for developing strategies to identify houses with potential problems, and ultimately for improving test methods.

To that end, in consultation with the Energy Commission Project Manager, the project team developed a work plan designed to fill gaps in the literature review. This simulation effort was accomplished in four major tasks:

1. Used simulation tools to identify physical parameters or combinations of parameters that contribute most to backdrafting and combustion spillage in appliance venting configurations that are relevant to California homes.
2. Identified common California appliance and home configurations that could be susceptible to backdrafting and spillage, and must therefore be studied to evaluate risk.
3. Determined statistics (frequency and duration) for depressurization events for home configurations selected in Task 2. Through simulation, determine the depressurization distribution of homes using weather patterns and mechanical exhaust operating schedules. Distributions and schedules of home depressurization levels will be combined with draft potentials to estimate the frequency of spillage over a typical meteorological year for California climates.
4. Identified problematic situations for combustion appliances when tightening homes. Through simulation, determine spillage frequency thresholds that provide an adequate margin of safety for health protection. Combine spillage thresholds with depressurization frequency estimates to develop guidance on diagnostic procedures that will ensure safe and robust venting.

The following describes these tasks in further detail.

Task 1. Identify key physical parameters associated with spillage

The purpose of Task 1 was to determine key physical parameters that lead to backdrafting and spillage. A critical first step in this task was to validate one or both of FLUESIM and VENT-II, which are computer programs designed to analyze natural draft and induced draft combustion appliance vent-system operation. Validation was to be primarily based on experimental data collected from Pacific Gas and Electric's (PG&E) Stockton, California training home for combustion safety. This validation work was necessary because the project team could not obtain adequate validation documentation for either package.

Simulations for predicting combustion spillage first focused on venting systems that purportedly meet National Fuel Gas Code requirements.⁵ After investigating code compliant homes, the effects of undersized and oversized vent systems on combustion spillage were explored along with different vent material types (ceramic vs. metal). The following physical parameters were varied in the simulation to determine their effects on vent pressure and vent mass flow-rate:

- House depressurization
- Burner size
- Amount of excess combustion air

5 NFPA. 2012. *National Fuel Gas Code, NFPA 54/ANSI Z223.1*. Quincy, MA: National Fire Protection Association.

- Frictional losses in the system due to bends and horizontal sections
- Vent cap design (friction)
- Difference between indoor and outdoor temperature

Task 2. Identify House Characteristics and Configurations

The purpose of Task 2 was to identify house characteristics and configurations common to the California housing stock for use in simulations described in Tasks 3 and 4. Through Task 2, the project team identified the following characteristics commonly found in the California housing stock: house size, occupancy, mechanical exhaust ventilation, house leakage, combustion appliance type, combustion appliance location, appliance usage patterns. Methods that the team used for collecting house characteristic and configuration data are described in the following sections.

- **House size, occupancy, and mechanical exhaust ventilation**

This project primarily focused on single-family houses. Three house sizes were to be studied: one small single story house, one medium single story house, and one large two story house. House sizes, the number of residents, and the number and type of mechanical exhaust ventilation appliances were chosen based on information from the existing California housing stock taken from the Residential Appliance Saturation Survey (RASS)⁶ funded by the Energy Commission.

- **House leakage**

The project team selected a range of air-tightness values for each house to simulate existing tightness conditions and tightness after retrofitting. House leakage information was initially to be selected based on size and location of the home. Houses were “tightened” as much as combustion safety allows.

- **Combustion appliance type**

Vented combustion appliances selected in houses represented appliances targeted in existing combustion appliance safety tests, which include natural draft water heaters, natural draft furnaces, induced draft furnaces, wall furnaces, and floor furnaces. Information from the RASS was used to select a range of appliance capacities for the three houses based on house size and location within the state. The appliance capacity was used in Task 4 to determine indoor air quality during combustion spillage events.

- **Combustion appliance location**

The project team could not find statistical data about the locations of water heaters and furnaces in California houses. To address this deficiency, the team conducted an expert

⁶ Kema Inc. 2010. “2009 California Residential Appliance Saturation Study”, *Technical Report CEC-200-2010-004*, prepared for the California Energy Commission.

elicitation by reaching out to building professionals with knowledge of the California housing stock. In particular, the team gathered information by surveying 15 to 20 building experts, including but not limited to the following categories: service technicians at the major California gas utilities; heating, ventilating, and air-conditioning (HVAC) and plumbing contractors; architects; home energy raters; and weatherization contractors. The survey primarily focused on combustion appliances located in the occupiable space. Appliances located in the attic or crawlspace were not considered because they are essentially outside the occupiable space and are less likely to spill exhaust gases and cause related indoor air quality problems.

- **Appliance usage patterns**

Appliance usage patterns were determined based on the number of occupants and size of home from the RASS. Energy usage patterns supplied by local gas companies were also used to estimate usage patterns. Gaps in information were filled in by conducting online surveys or by selecting reasonable patterns.⁷

Task 3. Simulate house depressurization

During Task 3, the project team used one year of weather data to simulate the annual range of wind and outdoor temperature effects on house depressurization. The simulations included 5 to 10 house configurations identified from Task 2 with mechanical ventilation and occupant patterns to estimate depressurization patterns over the course of one year in each case. Completion of this task provided home depressurization distributions to be used in Task 4. These statistical distributions were also valuable in showing how frequently a house exceeds maximum depressurization limits.

Task 4. Simulate pollutant concentrations

During Task 4, the project team parametrically explored how emission rates, spillage time, and house characteristics affect occupant health and identify appliance emission thresholds that maintain safe operating conditions. In particular, using data collected from or generated by Tasks 2 and 3, the team simulated the frequency and duration of spillage events over the course of one year to determine the risk associated with the spillage events. The simulations focused on houses that meet requirements set out by the California Mechanical Code⁸ and the National Fuel Gas Code⁹. Occupant health and safety were based on pollutant exposure and

7 Klug, Victoria L., Agnes B. Lobscheid, and Brett C. Singer. 2011. "Cooking Appliance Use in California Homes – Data Collected From a Web-Based Survey". *Lawrence Berkeley National Laboratory Report, LBNL-5028E*.

8 CBSC. 2010b. "California Mechanical Code: California Code of Regulations, Title 24, Part 4". California Building Standards Commission. Philadelphia, PA: International Association of Plumbing and Mechanical Officials.

9 NFPA. 2012. *National Fuel Gas Code, NFPA 54/ANSI Z223.1*. Quincy, MA: National Fire Protection Association.

were determined using federal or California Environmental Protection Agency ambient air quality standards¹⁰ for carbon monoxide (CO) and nitrogen dioxide (NO₂). More specifically, the team investigated the change in pollutant levels, through simulation, when the following parameters were varied:

- House and combustion appliance zone volume.
- House and combustion appliance zone air tightness.
- Appliance burner size.
- Exhaust concentration/emission rate (based on available data).
- House and combustion appliance zone depressurization.
- Burner usage (e.g., minutes of continuous or frequent intermittent firing).

For each parameter varied, the project team estimated the duration of spillage required to reach regulated airborne levels for CO and NO₂, assuming that all of the exhaust emissions from the appliances enter the house.

2.4 VENT-II Validation

As described in Appendix B, the project team's initial simulation efforts focused on VENT-II,^{11,12} because it has been used to generate vent sizing tables in the National Fuel Gas Code.¹³ Validation analysis consisted of simulating vent pressure, vent temperature, and vent mass flow-rate of the water heater and furnace in PG&E's test home located at their Stockton Training Center. Simulated results were compared to experimentally measured results for conditions in which the appliance spills and conditions when the appliance is venting properly. The team also carried out additional validation work for systems installed in a few local houses where the systems could be characterized as needed for the model comparison. The team found that although VENT-II provides a first step towards modeling vent systems, further development is required to make it reliably predict spillage caused by depressurization.¹⁴ As such, because

10 EPA. 2012. "Environmental Protection Agency, Clean Air Act". Retrieved May 17, 2012 from <http://epa.gov/oar/caa/title1.html#ia>.

11 Detty, D.W., S.R. Mawalkar, and S.W. McKeown. 1998. "VENT-II User's Guide, Version 5.0". *GRI Technical Report 98/0402*. Chicago, IL: Gas Research Institute.

12 Rutz, A.L., R.D. Fischer, and D.D. Paul. 1992. "Presentation of the VENT-II Solution Methodology". *GRI Technical Report 92/0149*. Chicago, IL: Gas Research Institute.

13 NFPA. 2012. *National Fuel Gas Code, NFPA 54/ANSI Z223.1*. Quincy, MA: National Fire Protection Association.

14 The project team did not carry out similar work using the FLUESIM computer program. Although FLUESIM is a powerful whole-house simulation tool, it requires 180 user inputs to fully describe the system and conditions being simulated, which made it impractical to validate within the project budget.

VENT-II could not be used as planned, the team changed its simulation plans further, again in consultation with the Energy Commission Project Manager.

2.5 Spillage, Airflow, and Yearly Distribution Simulation Studies

Appendix C describes the project team's simulations in detail. In particular, Section C2 provides the pollutant exposure limits that the team used in its modeling studies. Next, Section C3 describes a basic pollutant transport model, which forms the basis for the team's three main simulation studies. This simplified box model yielded insights into the role of variables such as the house volume, air change rate, and other factors that affect the generation and transport of combustion gases.

In particular, Sections C4, C5, and C6 describe three related simulation studies, which the project team designed to better understand the risk associated with house depressurization and combustion spillage, and to provide a solid knowledge base for future development of improved diagnostics. These sections are broken down into the following:

- The *spillage* study in Section C4 was designed to bound the problem under realistic conditions. It shows the *time evolution of indoor concentrations* when a combustion appliance is spilling under a *constant* house depressurization, using realistic values for the house size, air tightness, emission rate, and emission duration. This study did not, however, specify the *cause* of the depressurization.
- The *airflow driver* study in Section C5 was designed to *relate depressurization to airflows*. It examines, under *steady-state* conditions, how wind, indoor-outdoor temperature differences, and mechanical ventilation combine to establish the pressures and flows that determine backdrafting. This study identified the key parameters that affect *vent flow reversal*, but did not examine the resulting indoor concentrations.
- The *yearly distribution* study in Section C6 was designed to combine the airflow and concentration models under realistic weather conditions. It drives an indoor concentration model using observed yearly weather data from 16 California climate zones. This puts the results of the other two simulation studies into context, by accounting for the actual distributions of the wind and temperature conditions that help set airflow.

Chapter 3, which follows, highlights the results of the project team's literature review and simulation efforts. Detailed results are included in Appendices A through D.

CHAPTER 3:

Results

3.1 Literature Review

As described in the project team's literature review (Appendix A), current codes and standards related to combustion appliance installation and venting (e.g., the National Fuel Gas Code¹⁵ and the California Residential Code¹⁶) provide little information on assessing backdrafting or spillage potential. A draft test is recommended after an appliance is installed, but the appliance is only required to establish draft within five minutes after startup. Recommended solutions or repairs are not provided for appliances that do not establish draft. The National Fuel Gas Code provides vent-sizing requirements intended to ensure that combustion appliances vent properly. However, not all residential venting systems are code compliant. Some energy retrofit protocols include recommendations for updating venting systems to meet code requirements, but this recommendation is not adopted by all energy retrofit practices.

The Canadian General Standards Board "Spillage Test" standard (CAN/CGSB-51.71)¹⁷ and the American Society for Testing and Materials' (ASTM) E1998 guideline¹⁸ (originally published in 1995 and 1999, respectively) were the first comprehensive documents released for assessing depressurization induced backdrafting and spillage from vented combustion appliances. CAN/CGSB-51.71 is now called the "Depressurization Test". It provides protocols for determining if air-moving devices in a dwelling (i.e., exhaust fans) impair normal venting of combustion appliances. ASTM E1998 now provides guidance for assessing depressurization-induced backdrafting and spillage. It contains four stress tests and two monitoring protocols. Institutions such as the Building Performance Institution (BPI) and the Residential Energy Services Network (RESNET) have created commonly practiced combustion safety standards implementing some of the methods described in CAN/CGSB-51.71 and ASTM E1998. However, the Building Performance Institute (BPI) and RESNET only include stress test procedures for vented appliances (no monitoring), require additional measurements for carbon monoxide, and do not require code compliance.

Retrofit companies, weatherization programs, and local utility companies commonly use standards created by BPI and RESNET, but some have recognized the need to include

15 NFPA. 2012. *National Fuel Gas Code, NFPA 54/ANSI Z223.1*. Quincy, MA: National Fire Protection Association.

16 CBSC. 2010c. "California Residential Building Code: California Code of Regulations, Title 24, Part 2.5". California Building Standards Commission. Washington, DC: International Code Council.

17 CGSB. 2005. *Depressurization Test, CAN/CGSB-51.71*. Gatineau, ON: Canadian General Standards Board.

18 ASTM. 2011. *Guide for Assessing Depressurization-Induced Backdrafting and Spillage from Vented Combustion Appliances, E1998*. West Conshohocken, PA: ASTM International.

additional safety precautions and code compliance requirements. For example, the California Building Performance Contractors Association recently released a combustion appliance safety testing guideline¹⁹ that includes: (1) a visual safety inspection (e.g., ensuring vents are properly connected, no rust or damage), (2) BPI's combustion safety protocols, (3) protocols for unvented appliances (i.e., unvented heaters, stovetops, and ovens), (4) appliance installation code compliance, and (5) combustion ventilation air requirements. This guideline contains the most complete protocols for assessing combustion appliance safety and goes beyond concerns related to depressurization-induced backdrafting and spillage.

A substantial amount of research has been conducted to assess diagnostics for depressurization-induced backdrafting and spillage from combustion appliances. Much of the research compares results from stress tests to one-week of monitoring and these comparisons were performed on houses dissimilar to the majority of California houses. This research generally concludes that stress-induced tests should be interpreted with caution, because these tests tend to overestimate the number of spillage prone houses and results vary significantly with outdoor conditions. The authors of one study²⁰ recommended that an appliance should have to fail multiple (specific number not specified) stress tests before it is considered spillage prone.

Results from monitoring in homes that failed stress tests showed that events of sustained spillage were extremely rare. However, the one-week of monitoring that occurred in most of the published studies may be too short to reliably conclude that the studied appliances and houses will never have spillage incidences over the course of a typical year. Before making definitive conclusions about the accuracy of the stress-induced test results and frequency of spillage events, several authors recommend monitoring for longer periods of time. Additionally, extensive monitoring has not been conducted in houses that pass stress-induced tests to assess the rate at which appliances passing stress tests actually backdraft or spill. Therefore, the reliability of the stress tests to identify all houses that are at risk is unresolved.

In the rare cases when spillage was observed in monitored homes, events typically lasted 1 to 2 minutes during initial operation of the appliance. However, in three cases,²¹ continuous spillage occurred over 3 to 12 hour periods. Two studies^{22,23} concluded that properly sized venting

19 CBPCA. 2012. *Combustion Appliance Safety Testing Guidelines, March 2012*. Oakland, CA: California Building Performance Contractors Association.

20 Grimsrud, D.T., D.E. Hadlich, M.D. Koontz, R.J. Hemphill, N.P. Leslie, Z. Li, and N.L. Nagda. 1999. "Surveys on Depressurization-Induced Backdrafting and Spillage". *Proceedings of the 8th International Conference on Indoor Air Quality and Climate-Indoor Air '99*, Edinburgh, Scotland, 1.

21 Grimsrud, D.T. and D.E. Hadlich. 1995. "Residential Depressurization Protocol Development and Field Study". *GRI Technical Report 95/0324*. Chicago, IL: Gas Research Institute.

22 Bohac, D. and M. Cheple. 2002. "Ventilation and Depressurization Information for Houses Undergoing Remodeling". Minneapolis, MN: Final Report for the Minnesota Department of Commerce State Energy Office.

systems, complying with existing codes and standards, are less likely to spill. These studies also recommended that emphasis be placed on improving venting performance to prevent combustion spillage.

When monitoring houses, several authors^{24,25,26,27,28,29} indicated that vent pressure is not a good indicator of spillage, because positive pressures often result from downdrafting (combustion appliance off) and not backdrafting or spillage (appliance on). Additionally, temperature monitored in the spillage zone may be affected by thermal radiation from gases flowing near the draft diverter, providing false spillage measurements.

Generally, research investigating the effects of weather variation on stress-induced tests is limited. One study³⁰ showed that houses were more likely to fail stress-induced tests during *low wind speeds* rather than during high wind speeds. This study did not find a definitive correlation between outdoor temperature and stress-induced tests, but a different study³¹ showed that spillage failure increased significantly when outside temperatures were greater than 40°F.

The objectives of available test methods, both stress and monitoring, are not clearly defined. Implicitly, the tests apply a dichotomous criterion, with any occurrence of backdrafting or spillage regarded as a failing condition. In practice, the likelihood and frequency of such events in any given home has a statistical element that is essential to defining the health and safety risk. Likewise, variations in the pollutant generation characteristics of various appliances

23 Fugler, D. 2004. *Residential Combustion Spillage Monitoring, Research Highlight: Technical Series 04-101*. Ottawa, Ontario: Canada Mortgage and Housing Corporation.

24 Grimsrud, D.T. and D.E. Hadlich. 1999. "Initial Surveys on Depressurization-Induced Backdrafting and Spillage: Volume II - Twin Cities, MN". *GRI Technical Report 99/0187*. Chicago, IL: Gas Research Institute.

25 Koontz, M.D., S. Natarajan, N.L. Nagda, and S.N. Nagda. 1999. "Initial Surveys on Depressurization-Induced Backdrafting and Spillage: Volume I - Washington, DC and Omaha, NE". *GRI-99-0186*. Chicago, IL: Gas Research Institute.

26 Koontz, M.D., S. Natarajan, N.L. Nagda, and Z. Li. 2001. "Follow-Up Survey on Depressurization-Induced Backdrafting and Spillage in Omaha Residences". *GRI-01-250*. Chicago, IL: Gas Research Institute.

27 Bohac, D. and M. Cheple. 2002. "Ventilation and Depressurization Information for Houses Undergoing Remodeling". Minneapolis, MN: Final Report for the Minnesota Department of Commerce State Energy Office.

28 Koontz, M.D. and N.L. Nagda. 2002. "Depressurization-Induced Backdrafting and Spillage: Implications of Results from North American Field Studies". *ASHRAE Transactions*, 108.

29 Nagda, N.L., Z. Li, M.D. Koontz, and S. Natarajan. 2002. "Depressurization-Induced Backdrafting and Spillage: Assessment of Test Methods". *ASHRAE Transactions*, 108.

30 Koontz et al. 2001.

31 Bohac, D. and M. Cheple. 2002.

impact the actual risks associated with backdrafting and spillage. Yet none of the current diagnostic procedures address the statistical nature of the risk, nor do they account for variations in risk associated with differences in pollutant generation across appliances.

Existing simulation software, such as VENT-II, purportedly can assist with the design and analysis of residential combustion appliance venting systems to predict backdrafting or spillage using whole house system inputs (e.g., envelope airtightness, combustion appliance and ventilation system operation, chimney or vent design, weather effects). As such, this software could be useful for creating a more robust diagnostic method for field use. However, the software is not currently being used for this purpose (nor, as described in Appendix B, is it reliable enough to do so as it turns out).

The following are key findings and gaps in the literature that the project team reviewed:

- Short-term induced test methods can overestimate the occurrence of backdrafting and spillage.
- Short-term test methods including worst-case depressurization tests implicitly set the strict standard that vented appliances should *never* spill for more than a short period at burner ignition.
- Short-term tests are designed to evaluate venting performance of combustion appliances during the winter months.
- Existing test methods do not explicitly address the frequency of spillage under normal operating conditions, nor do they identify the key contributors to spillage in a given house.
- Standards addressing acceptable spillage durations are inconsistent.
- Venting systems that meet National Fuel Gas Code³² requirements are more likely to vent properly.
- CO output under downdraft conditions can be reduced if combustion appliances are properly cleaned and tuned.
- Water heaters have greater backdrafting potential than furnaces. However, available data indicate that conventional storage water heaters very rarely have high CO emissions.
- Simulation software tools have not been utilized commensurate with their potential value to improve understanding of venting performance.
- Most existing research has been conducted on houses dissimilar to California houses.

32 NFPA. 2012. *National Fuel Gas Code, NFPA 54/ANSI Z223.1*. Quincy, MA: National Fire Protection Association.

- Effects of wind on venting performance and house depressurization have not been explored adequately.
- Effects of vent-cap designs on venting performance have not been explored adequately.
- Effects of outdoor temperature on venting performance were not fully explored.
- Existing research has not adequately explored the impact of the many other relevant physical parameters on backdrafting and spillage (e.g., mechanical ventilation operating schedules, burner rating).

3.2 VENT-II Validation

As described in Appendix B, the project team carried out a validation of VENT-II^{33,34} to assess whether it could be used to predict combustion appliance zone (CAZ) depressurizations leading to combustion spillage (spillage depressurization). The validation involved comparing simulated results from VENT-II with experimental data from four vent systems. From this study, the team came to the following conclusions:

- VENT-II correctly predicted spillage depressurization for appliances operating in cold and mild outdoor conditions, but could not accurately predict spillage depressurization for hot outdoor conditions. This result indicates that VENT-II is not reliable for predicting spillage depressurization over the entire year, especially where hot outdoor conditions occur.
- For a single-appliance vent system, moving vent sections from the common vent to the connector vent in VENT-II changes the predicted spillage depressurization, and should not occur.
- The algorithm used in VENT-II's solver needs further investigation. In many cases, the solver converged to an incorrect solution at a given time step, but would correct itself for the next time step, leading to inconsistent results.
- VENT-II provided inconsistent errors when changing CAZ depressurization for a model. In some cases, a specific CAZ depressurization would cause the solver to fail, but increasing or decreasing the CAZ depressurization slightly (± 0.1 Pa, 0.0004 inches water column [in. w.c.]) would provide a complete solution.
- Due to inconsistent errors with the solver, an exact spillage depressurization could not be determined for a few cases. Therefore, VENT-II may not properly identify appliances that are spilling in practice.

33 Detty, D.W., S.R. Mawalkar, and S.W. McKeown. 1998. "VENT-II User's Guide, Version 5.0". *GRI Technical Report 98/0402*. Chicago, IL: Gas Research Institute.

34 Rutz, A.L., R.D. Fischer, and D.D. Paul. 1992. "Presentation of the VENT-II Solution Methodology". *GRI Technical Report 92/0149*. Chicago, IL: Gas Research Institute.

Although VENT-II provides a first step towards modeling vent systems, further development is required to produce a reliable program that can correctly predict spillage caused by depressurization. From this study, the project team recommended that VENT-II's solver be investigated further and more detailed instructions be provided when modeling single-appliance vent systems.

3.3 Spillage, Airflow, and Yearly Distribution Simulation Studies

As described in Appendix C, the project team used computer simulations to conduct three studies designed to better understand the risk associated with house depressurization and combustion spillage. The spillage study used simulations to explore the time evolution of indoor concentrations when a combustion appliance is spilling with constant airflows. In this study, house volume, air tightness, depressurization, and spillage rate and duration were varied. The airflow driver study used simulations under steady-state conditions to assess which airflow-related parameters (e.g., wind, indoor-outdoor temperature differences, and mechanical ventilation) are most important in establishing the pressures and flows that determine backdrafting. The yearly distribution study combined the airflow and concentration models under realistic weather conditions to assess the annual statistical variation of pollutant concentrations. Results from the simulation studies provide a better understanding of depressurization-induced backdrafting and conditions such as stalling of vent flows that can lead to hazardous indoor pollutant concentrations.

As described in Section C2 of Appendix C, a short-term “stress” test can provide a snapshot of pressure changes in a house when one or more exhaust fans operate in the house. However, the simulation studies described in this report raise a number of questions about the suitability of existing stress tests, and the guidelines for their interpretation. Of particular concern is that the tests are fundamentally flawed and are not nearly as useful as people think for the purpose of finding problem situations. For example, in some cases, they are needlessly conservative, potentially leading to unnecessary interventions in houses that do not pose a health risk to their occupants. In other cases, they are not conservative enough, such as their neglecting other harmful combustion pollutants (e.g., nitrogen oxides).

Broadly speaking, the simulations reported here suggest that current limits on fan-induced pressure change, such as those listed in Tables C1 and C2 of Appendix C, should be considered only rules of thumb that probably lead to overly cautious air tightening and remediation. Furthermore, these limits do not necessarily represent worst cases that occur at modest rather than maximum depressurization. Until now, it seems that there has been little recognition that maximum depressurization *increases ventilation and reduces concentrations*.

Consider, for example, the -5 Pa depressurization limit for a furnace and water heater sharing a vent. The project team's simulations showed that a house may exceed or fall short of this limit, depending on its air tightness, the exhaust fan size, the weather at the time of the test, and other variables such as the resistance of the vent shaft to flow relative to that of adventitious leaks in the house envelope. Note that these simulations, however, probably over-estimate the risk of spillage. In practice, the -5 Pa depressurization limit derives from field observations, so the team

believes that accounting for the thermal dynamics would show that the supermajority of houses are safe at that limit. Therefore, the blind application of the -5 Pa depressurization limit, without accounting for factors such as the weather at the time of the test, and the historical distribution of annual wind and outdoor temperature at the site, probably over-estimates the possibility of backdrafting. As a result, the limit probably causes unnecessary remediation, and possibly discourages energy contractors from tightening houses as much as could be achieved.

Rather than focusing on depressurization, the more important metric involves the *indoor concentrations* that result from combustion gas spillage. Broadly, there are three types of hazard that can result:

1. **Life-safety hazard** when CO reaches concentrations above 100 parts per million (ppm). 100 ppm is not itself a life safety hazard, but rather a lower threshold on the range of potentially very serious outcomes. It is unacceptable to reach these levels and combustion safety test and assurance procedures should have multiple safeguards to ensure this level is not reached. Even if one thing goes terribly wrong or one very unlikely event occurs, these safeguards should ensure that these conditions will not occur.
2. **Acute health hazard** when concentrations reach levels exceeding health based standards for outdoor air. These are 9 ppm over 8 hours or 20 to 35 ppm over a 1 hour average. These levels are set for sensitive subpopulations. Outdoor air in many places in the United States has pollutant levels that exceed the analogous health based standards for particle matter (e.g., PM_{2.5}) and ozone. The goal should be that these standards are not exceeded other than under unusual or infrequent conditions. Having these conditions exceeded up to a few times per year is probably tolerable - though, of course, still undesirable - failure rate. It would be unnecessarily cautious to spend a lot of money to make sure that these levels are never reached.
3. **Chronic health hazard** resulting from frequent spillage that leads to indoor pollutant levels that comprise a substantial fraction of the chronic health standard level for NO₂ or are on the order of a few parts per million (ppm) averaged over days to weeks for CO. For NO₂, the concern is about the “substantial fraction” because there are other sources of exposure including outdoor air. For CO, the concern is about levels of a few ppm because there are plausible mechanisms and adequate research isn’t available. Also, CO should not be emitted regularly into houses at levels that produce a few ppm averaged over time.

Computer models can help extrapolate field measurements of parameters such as fan-induced depressurization (Δp_f) into anticipated long-term behavior, for example, the likelihood of backdrafting, and more importantly the consequent indoor air concentrations and exposures. Simulations may also help identify a progression of tests for successively evaluating the risks of backdrafting and vent stall. Such a progression would move from simple screening tests, to more accurate but potentially more difficult assessments of houses deemed at risk of significant indoor concentrations due to spillage from a combustion appliance.

This report begins to explore these possibilities, not in terms of what acceptable pollutant levels should be (which is a policy decision), but rather in terms of what appliance emissions can be tolerated and what concentrations can occur statistically. However, its conclusions are not definitive, in part because the available models do not account for the thermal performance of the vent shaft, including the dynamics associated with heating the vent (something the project team had initially hoped VENT-II could do).

In summary, the simulations that the project team performed show the following:

- Conventional wisdom is correct in that, all else being equal, tightening the house envelope does indeed increase the danger that an exhaust fan will cause backdrafting of a naturally-ventilated combustion appliance.
- For short (less than or equal to 5 minutes) spillage events, the combustion safety protocols are protective against life threatening CO conditions, even in the case when the appliance is malfunctioning and has repeated intermittent spillage. However, the protocols likely establish CO thresholds that are too conservative for large houses with infrequent spillage events.
- Prolonged or continuous spillage events in a moderately airtight house could result in an acute hazard if the burner is malfunctioning. Therefore, combustion safety protocols should ensure that conditions of sustained spillage and high emissions do not exist without high ventilation.
- Reaching life threatening conditions in a moderately tight house with a natural draft appliance is rare and almost impossible for an induced draft appliance. However, in a very tight house (with an air change rate at 50 Pa, a_{50} , of 2 air changes per hour or tighter), the combination of low air change rate and increased risk of spillage significantly increases the potential for prolonged pollutant exposure that could lead to a life-safety hazard. Therefore, the project team recommended that all combustion appliances in very tight houses be direct vent or installed outside the living space.
- Similar to CO, NO₂ in combustion spillage from natural draft and induced draft appliances may also present an acute hazard and should be included for combustion safety assurance. Because NO₂ concentrations from the appliance may be difficult to measure, however, the project team instead recommended measuring the total oxides of nitrogen (NO_x) and using an upper limit, or a fraction of the NO_x, that is characteristic to the appliance (i.e., about 10% or less of NO_x exhausted from storage water heaters is NO₂).
- The most dangerous conditions result from *stalled flow* in the appliance vent shaft. While strong depressurization and negative (inward) airflows bring combustion products into the occupied space, these airflows also *dilute* the combustion products. This is an important phenomenon that has not been recognized until now.
- Fan-induced pressure change - the metric used in current stress testing regimens - does not directly assess whether flow will stall or reverse in the vent shaft. The pressure

change needed to reverse flow in the vent shaft depends not only on fan-induced pressure differences, but also on naturally-induced weather-related pressure differences, which vary throughout the year.

- A large enough fan-induced pressure change does imply backdrafting. However, by the time fan-induced pressure change is large enough to guarantee backdrafting, it is almost never of concern in terms of indoor air quality, due to the dilution that it contributes by outdoor air entering through the vent.
- Because the exhaust fan forces a minimum airflow through the occupied space, it (along with the generation rate for the combustion appliance) establishes an effective maximum concentration in the space (the fan-limited steady-state concentration).
- For the conservative model used in the project team's simulations, the fan-limited steady-state concentration for a fairly small exhaust flow rate is in the neighborhood of the Consumer Product Safety Commission (CPSC) limit of 25 parts per million by volume (ppmv). Increasing the exhaust flow only reduces the concentration ceiling established by the fan.
- Regardless of fan-induced depressurization, the building professional should always ensure that the appliance burner is clean, the appliance is functioning properly, the vent system is connected to the appliance, and draft is established in a short period of time.

The project team's simulations probably are overly conservative, for a number of reasons:

- They do not account for combustion-related heating in the vent shaft, which will tend to encourage outward flow.
- The houses considered are small compared to the norm. Larger houses, for a fixed air change rate, allow more flow through adventitious leaks, and therefore (all else being equal) have a lower chance of backdrafting. Furthermore, larger houses provide a greater volume of air for diluting combustion products in the event backdrafting does occur.
- The assumed combustion appliance size was not adjusted for the climate zone, and therefore may be large for many of the simulated houses. This gives a larger assumed generation rate than realistic, especially for warmer climate zones, which tend to have greater problems with backdrafting.
- The combustion appliance is assumed to operate, at best, at the outer limit of the acceptable range of generation rates.
- The combustion appliance is assumed to operate continuously, thus producing a greater mass of combustion product than realistic.

However, a number of modeling approximations mean that the project team's simulations may not always over-predict indoor concentrations:

- The well-mixed assumption under-estimates exposure for occupants close to a combustion source. Conversely, it can over-estimate exposure for thermally-stratified combustion products.
- Ignoring the relative timing of exhaust fan and appliance operation misses potential cross-correlation effects. For example, running an exhaust fan at the same time as a combustion appliance, and shutting it off when the appliance shuts off — as might be expected for a shower fan and water heater — would tend to increase the predicted long-term average concentrations compared to those reported in the cyclic simulations of Section C4 of Appendix C.
- The airflow driver and yearly distribution studies assume wind always creates suction at the vent cap, no matter what the wind direction. This tends to decrease the likelihood of backdrafting.

3.4 Implications

The simulations, and the analytic results from the box model that the project team developed, focus attention on two aspects of the house-appliance system: (1) the combustion appliance is the best point of control of indoor air quality problems; and (2) the proper focus of a field test is not what happens when all the exhaust fans are operating at once, but rather what minimum exhaust fan flow is needed to just reverse flow in the vent shaft.

While backdrafting always should be avoided, it is not necessarily catastrophic. In cases where mechanical exhaust is strong enough to cause spillage, limiting the generation rate of the combustion appliance will always limit the concentration of combustion products in the occupied space. See, for example, Equation C26 in Appendix C, which gives the fan-limited steady-state concentration.

The critical exhaust fan flow rate is that which just reverses flow in the vent shaft. At zero vent shaft flow, combustion products enter the house, but dilution due to air brought in by the fan is at a minimum. Increasing the exhaust flow brings more outside air into the house (through both the vent shaft and the adventitious leaks), and therefore decreases the fan-limited steady-state concentration. Therefore, the maximum exhaust fan flow rate, while it does give the highest likelihood of backdrafting, does not correspond to the worst consequences of backdrafting.

Simulations similar to those reported here could be used as part of a future screening tool, either to help translate field measurements into a risk assessment, or to guide the field tests toward an appropriate level of testing. For example, Figure C5 in Appendix C suggests how pre-tabulated results could form the basis of a screening test that establishes, for a given house performance under a depressurization stress test, the maximum acceptable generation rate for a combustion appliance.

A more detailed test might attempt to force the flow in the appliance vent shaft to zero. Comparing the weather conditions at the time of the test, against the expected annual weather, would give an estimate of the worst-case exhaust flow (i.e., the smallest exhaust flow that could be expected to just stall a drafting vent shaft). If the exhaust fans in the house are able to

establish that flow, then the test would proceed to a second stage. The worst-case exhaust flow, combined with an estimate of the effective mixing volume of the house, would imply a maximum “safe” source rate at which the combustion appliance could generate pollutants. Thus, if the exhaust flow needed to create zero vent shaft flow under worst-case weather conditions was very high, then the test protocol could account for dilution when establishing the critical performance of the appliance. Conversely, if only small mechanical exhaust was required to reverse flow in the vent shaft, the house would be deemed to have a higher risk and further testing or mitigation would be needed.

The feasibility of such an approach hinges on: (1) the ability to easily and reliably find the cutoff exhaust flow at which the vent shaft stops drawing; and (2) whether, from a statistical view, such a test imposes an overly conservative limit on the combustion source rate. This study cannot, of course, speak to the first question. However, the project team noted that the simulations shown in Figure C13 of Appendix C assume a small house relative to most California homes, a large combustion appliance relative to the size of the house, a source rate at the edge of the American National Standards Institute (ANSI) limit, and a not unreasonably large exhaust fan. These assumptions, perhaps not coincidentally, lead to worst-case concentration estimates very near the CPSC limits. This result suggests that an appropriately sized and well-tuned appliance should be able to pass a test that seeks to limit the CO source rate based on the house’s worst-case ventilation characteristics.

3.5 Simulation Improvements Needed

Before simulations can be used to guide testing, or to safely assess the risks associated with a particular house, the models would have to be improved. As noted above, the greatest limitation of the simulation studies performed here is the lack of a coupled airflow-thermal model. The model does not account for the temperature of air in the vent shaft, which due to convection heat transfer at the shaft surface, depends on the airflow rate. A useful model must include these and other thermal effects, such as convective and radiative heat losses in the attic. Unfortunately, currently available tools do not incorporate the required thermal physics, or do not represent them adequately.

Furthermore, a coupled airflow-thermal simulation tool would have to account for the dynamics associated with heating in the vent shaft over the course of an entire year. For example, even if an operating appliance can maintain draft when an exhaust fan turns on, it may not be able to establish draft if the fan already was running when the appliance begins to heat up. That is, the sequence of events matters.

In principle, a simulation tool could assume that the vent shaft was able to establish draft, and then use steady-state thermal and airflow models to find consistent flows and temperatures under that assumption. The results might correspond to the case that an operating combustion appliance already had established draft at the time the exhaust fan turned on. Such a steady-state analysis should be able to detect most cases where the exhaust fan was able to “pinch off” a drafting vent shaft (since the search for a consistent airflow-thermal solution would drive the

estimated vent shaft flow to zero, and hence would drive the estimated vent shaft air temperature towards some average of the room and outside temperatures).

Other model improvements do lie within the capabilities of the contaminant transport model that the project team used in its yearly distribution study (CONTAM)³⁵. These include: (1) refining the treatment of wind at the vent cap; (2) scheduling the combustion appliance; and (3) scheduling the exhaust fan. To be conservative, a model could simply make the exhaust fan turn on when the combustion appliance is on, and off when the appliance is off. This would partially relieve the need to choose absolute times at which the source turns on and off, since the relative schedule (intermittency and duration) matters most. However, interactions between the fan and appliance schedules, and the weather, still would have to be taken into account.

3.6 Recommended Changes to Combustion Safety Diagnostics

Using sealed combustion appliances or locating them outside the pressure boundary of the occupied space is one solution to reducing or eliminating health and safety risks associated with spillage. However, especially in retrofit situations, doing so may not be cost effective. In these cases, one needs to instead use a diagnostic procedure to assess the risks of spillage for the house and appliances as found and also as they might operate if retrofits (e.g., house air tightening) are implemented.

The following are recommended changes to current combustion safety diagnostics, based on the findings of the project team's literature review and simulation studies:

- 1. Eliminate comparisons of worst-case depressurization test results to threshold limits by appliance type.**

The current threshold limits by appliance type are not robustly applicable and the fan configuration for the worst-case scenario is typically so unusual that it does not represent an appropriate challenge condition.

- 2. Ensure that diagnostic protocols include inspections of air supply, appliance operation, and venting.**

Recognizing that the combustion appliance is the best point of control of indoor air quality problems, one should:

- Confirm that adequate outdoor air will be supplied to the combustion appliance zone (CAZ) at all times to support combustion and to prevent CAZ depressurization that can stall vent flow.
- Inspect appliance: confirm air inlet (if used) is open; look for evidence of spillage.
- Inspect vent to confirm integrity and code-compliant materials, sizing, and layout.

35 Walton, G.N., and W.S. Dols. 2010. *CONTAM User Guide and Program Documentation*. Gaithersburg, MD: National Institute of Standards and Technology. December. NISTIR 7251.

- Conduct induced backdraft CO test: measure air-free CO in appliance flue during induced backdraft, and verify that levels are below appropriate thresholds. This test provides a margin of safety by ensuring that even if there is backdrafting and spillage, CO levels in the flue during this event will not be above levels of concern (see comment below about ANSI standards for appliance CO). Backdrafting could be induced either by operating exhaust fans in the house, or by using a blower door. In either case, caution should be exercised to not depressurize the CAZ so much that flame roll out occurs.

3. **Include a draft test under challenge (but not worst case) depressurization conditions.**

The proper focus of a field test is not what happens when all the exhaust fans are operating at once, but rather what minimum exhaust fan flow is needed to just stall flow in the vent shaft. At zero vent shaft flow, all of the combustion products enter the house, but dilution due to air brought in by the exhaust fan(s) is at a minimum. However, one also needs to consider how often such a condition occurs.

This test replaces the worst-case depressurization test to identify appliances that cannot establish draft during coincident operation of exhaust fans. The challenge condition should represent one that could occur at a frequency of at least several times per month and, when it occurs, will commonly persist for long enough that emitting pollutants could build up to hazardous levels (typically on the order of an hour or more). To the extent that these exhaust devices are present, it should include operation of the clothes dryer, exhaust fans in all bathrooms that are used on daily basis, and the kitchen exhaust fan operating at a speed that is commonly used (including no operation if not used).

Because one should be concerned mostly about conditions that occur frequently or at least not infrequently, for this depressurization draft test, it makes sense to start with fan combinations that represent frequent use over periods of an hour or more. Dryers satisfy the criterion. Kitchen and bath fans also meet the criterion, since their use is so strongly encouraged. However, there are few cooking episodes that last even an hour and many bath fans have timers that limit the length of time that a fan runs. Conversely, there could be multiple showers in a row with ongoing use of a bath fan.

A fan combination for a *conservative* test might look like:

- Dryer, if within mixing volume of home.
- Kitchen fan operating on the highest setting with less than 3 sones³⁶ or at the lowest setting if none of the higher settings produce less than 3 sones. The rationale is that people infrequently use hoods at noisy settings, and would not tend to leave noisy hoods operating any longer than needed.

³⁶ Sone is a unit related to the *subjective* perception of sound loudness. It is used in standards such as ASHRAE 62.2 to specify upper limits for fan noise.

- Largest bath fan. The rationale for only one bath fan is that multiple showers or extended coincident use of multiple bathrooms might be uncommon.

A fan combination for a *less conservative* test could be similar, but with the largest bath fan operating only if it is quiet (less than 1 sone) and NOT on a timer. The rationale is that this fan would be turned off sooner than manual operation might otherwise cause.

4. Apply assurance procedures to *all* appliances used as heat sources in the house.

Combustion safety assurance should address *all* combustion appliance hazards, so this recommendation includes supplemental heating appliances. Since, by design, unvented appliances release exhaust gases directly into the living space – which is a mode of operation that combustion safety protocols are trying to diagnose – application of this recommendation without other provisions would mean that a house would not pass a combustion safety assurance test if unvented or vent-free combustion appliances are used as heating sources.

It may be warranted to consider whether engineered product safety features could be acceptable, and how the reliability and performance of those features could be measured in the field. This should not present a problem in California, which essentially disallows unvented heaters already. However, it would be a dramatic change for other U.S. locations. The decision on how to deal with this challenge should not compromise the fundamental risk management approach.

Stoves should be treated as any other heating source if there is no other heating source available or if there is evidence that the stove is used as a heating source.

5. Include kitchen ventilation in combustion safety assessments.

For combustion-powered cooking appliances, kitchen exhaust ventilation is the applicable venting system. The theoretical basis for treating these appliances differently than others – for which automatic and robust venting is required – is that cooking burners are typically smaller, used over shorter periods of time, and are not intended to be used unattended. If kitchen ventilation does not meet ASHRAE Standard 62.2³⁷ requirements and cannot be cost-effectively improved to meet 62.2, the homeowner should be alerted and provided with guidance to open windows or use other exhaust fans in the house when cooking. It may also be appropriate to have the homeowner sign a waiver.

6. Coordinate with ANSI to reduce allowable CO levels in new appliances.

Current failure thresholds for CO measured in the appliance flue are much lower than ANSI standards for air-free CO in new appliances. This creates an awkward situation in

37 ASHRAE. 2010. *Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings*, ANSI/ASHRAE Standard 62.2. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

which a new appliance that meets ANSI standards could fail a combustion safety test. New appliance CO standards could be lowered substantially based on the performance capabilities of modern appliances. Some combustion safety protocols currently use CO thresholds that are lower than needed for safety assurance. A harmonized new appliance standard will likely be much closer to the lower levels currently used by home performance combustion safety diagnostic protocols as a factor of safety assuming that appliance performance will degrade over time. Further work is needed, however, to determine the house airtightness threshold for which the home performance standards could be reduced in response to lower CO emissions.

7. Develop a condition assessment / calculation procedure that considers burner size, dilution volume, and air change rate.

The specified condition of concern would be one that produces backdrafting (preferably by identifying stalled flow in the appliance vent). The idea is to not worry about houses in which a small burner is spilling 100 percent of the combustion gases, but could not emit enough pollutant mass to produce a hazard because of the amount of dilution.

CHAPTER 4: Benefits to California

The most important benefit of this project is the new knowledge about risk-based approaches to combustion appliance diagnostics for protecting health and safety, all of which could ultimately be used to update California's Energy Code (Title 24, Part 6).³⁸ In particular, this task identified risk based metrics (e.g., vent flow stall rather than worst case depressurization) for better characterizing the circumstances necessary for safe operation of combustion appliances in houses. To that end, this task shows that worst case depressurization is the wrong metric, and shows that depressurization beyond that which corresponds to vent flow stall actually reduces indoor pollutant concentrations by providing dilution airflow through the vent.

In terms of the California Energy Code, this project also focuses on enabling increased airtightness and energy savings in home retrofits. From an energy standpoint, one-third to one-half of the space conditioning load in houses is attributable to infiltration through building envelope leaks; perhaps 25 to 50 percent of this load potentially could be reduced by improved airtightness, if new risk-based combustion safety diagnostics could show that this tightening can be done without endangering health or safety. At this point, however, specific airtightness targets to avoid spillage risks are not available, and future work is needed to develop the new diagnostics based on the findings reported here.

In terms of California Assembly Bill 32 (AB 32, Nunez, Statutes of 2006), which requires California to reduce its greenhouse gas (GHG) emissions to 1990 levels by 2020, retrofits enabled by the new risk-based diagnostic approaches would also help to reduce these emissions and their potential harmful effects. Improved diagnostics in turn could be used to help the State take a lead on GHG reducing retrofits, and to serve as a model for code authorities locally and nationally.

The results of this project ultimately will allow the Energy Commission and other agencies to initiate aggressive efforts through the Energy Code and AB 32 to set new, cost effective standards for the airtightness of existing homes. From a broader economic perspective, the knowledge developed in this task could ultimately facilitate more retrofits and more extensive retrofitting of homes, thus creating green jobs and reducing energy expenditures, which in turn makes consumer funds more available to purchase other commodities and services. Already, funding for this project has directly enhanced technical expertise at LBNL, and supported training for new scientists and engineers.

This project has resulted in several instances of public dissemination of this new knowledge. In particular, the results of the literature review and simulation work have been published as follows (as included in Appendices A through D):

38 CBSC. 2010a. "California Energy Code: California Code of Regulations, Title 24, Part 6". California Building Standards Commission. Washington, DC: International Code Council.

- Rapp, V.H., J.C. Stratton, B.C. Singer, and C.P. Wray. June 2012 (Revised August 2013). “Building Airtightness through Appliance Venting Standards: Assessment of Literature and Simulation Software Related to Combustion Appliance Venting Systems”. Lawrence Berkeley National Laboratory Report. LBNL-5798E.
- Rapp, V.H., A. Pastor-Perez, B.C. Singer, and C.P. Wray. 2013. “Predicting Backdrafting and Spillage for Natural Draft Combustion Appliances: A Validation of Vent-II”. ASHRAE HVAC&R Research Journal, Vol. 19, Issue 3, February. LBNL-6193E.
- Lorenzetti, D.M., V.H. Rapp, B.C. Singer, and C.P. Wray. September 2014. “Residential Combustion Gas Spillage: Impacts of Airtightness and Airflows on Indoor Air Pollutant Concentrations”. Lawrence Berkeley National Laboratory Report.

The literature review was also discussed with a group of combustion safety experts early in the project at a June 2012 meeting in San Antonio, Texas that was arranged by the Gas Technology Institute. The meeting title was “Best Approach to Combustion Safety in a Sealed Combustion World”, and was conducted under the auspices of the U.S. Department of Energy Building America program “Partnership for Advanced Residential Retrofit” (PARR). The results of the project team’s literature review were well received and the broad consensus was that the team was on the right track pursuing a risk based approach to combustion safety tests.

Other related dissemination activities have included the following industry-facing presentations and articles:

- Rapp, V. August 2013. “New Directions for Combustion Safety Testing”, LBNL Presentation at the “Data not Dogma” Conference, Goldendale, WA.
- Singer, B. and V. Rapp. November 2013. “Myths and Facts about Combustion Safety (Be Safe, Not Scared)”, LBNL Presentation at the Affordable Comfort Institute Regional Home Performance Conference, La Jolla, CA.
- Rapp, V., B. Singer, and I. Walker. February 2014. “10 Common Misconceptions About Combustion Safety”, LBNL Article in Home Energy.

This work has also resulted in an extensive online blog,³⁹ which is entitled “Are We Off Track With Combustion Safety Testing?”. The blog has attracted substantial participation from industry stakeholders.

39 Bailes, Allison. 2014. “Are We Off Track With Combustion Safety Testing?”. *Energy Vanguard Blog*. <http://www.energyvanguard.com/blog-building-science-HERS-BPI/bid/74136/Are-We-Off-Track-With-Combustion-Safety-Testing>. Accessed March 2014.

GLOSSARY

Term	Definition
AB	Assembly Bill
Ach	Change rate per hour
ACH50	Air Changes per Hour (ACH) at 50 Pa. Used as a measure of building airtightness
AFR	air/fuel ratio
AGA	American Gas Association
ANSI	American National Standards Institute
APT	Automatic performance testing
Appliance Flue	The passage(s) within an appliance through which combustion products pass from the combustion chamber of the appliance to the draft hood inlet opening on an appliance equipped with a draft hood or to the outlet of the appliance on an appliance not equipped with a draft hood.
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
ASTM	American Society for Testing and Materials
Backdrafting	The reversal of the ordinary (upward) direction of air flow in a chimney or flue when vented combustion appliances are operating
BPI	Building Performance Institute
CAS	Combustion appliance safety
Category Vented Appliance	An appliance that operates with a <i>non-positive</i> vent static pressure and with a vent gas temperature that <i>avoids</i> excessive condensate production in the vent.
Category II Vented Appliance	An appliance that operates with a <i>non-positive</i> vent static pressure and with a vent gas temperature that <i>can cause</i> excessive condensate production in the vent.
Category IV Vented Appliance	An appliance that operates with a <i>positive</i> vent static pressure and with a vent gas temperature that <i>can cause</i> excessive condensate production in the vent.
CAZ	Combustion appliance zone
CBPCA	California Building Performance Contractors Association
CBSC	California Building Standards Commission

Central Furnace	A self-contained appliance for heating air by transfer of heat of combustion through metal to the air and designed to supply heated air through ducts to spaces remote from or adjacent to the appliance location.
CFD	Computational Fluid Dynamics
CGSB	Canadian General Standards Board
Chimney	One or more passageways, vertical or nearly so, for conveying flue or vent gases to the outdoors.
Chimney Flue	The passage(s) in a chimney for conveying the flue or vent gases to the outdoors.
CMHC	Canada Mortgage and Housing Corporation
CO	Carbon monoxide
CO ₂	Carbon dioxide
Common Vent	That portion of a vent or chimney system that conveys products of combustion from more than one appliance.
CONTAM	Contaminant transport analysis
CPSC	Consumer Product Safety Commission
CSST	Corrugated Stainless Steel Tubing
CVEP	Cold Vent Establishment Pressure
Da	Available Draft (Pa)
Dp	Depressurization (Pa)
Dt	Theoretical Draft (Pa)
Direct Vent Wall Furnace	A system consisting of an appliance, combustion air, and flue gas connections between the appliance and the outdoor atmosphere, and a vent cap supplied by the manufacturer and constructed so that all air for combustion is obtained from the outdoor atmosphere and all flue gases are discharged to the outdoor atmosphere.
Draft Hood	A draft hood acts as a pressure break between the vent system and the appliance and eliminates stack action. Without draft, the vent could experience excessive draft, flame instabilities, and possibly pilot outage.
DOE	United States Department of Energy
Downdrafting	The reversal of the ordinary (upward) direction of air flow in a chimney or flue when no vented combustion appliances are operating.

Duct Furnace	A furnace normally installed in distribution ducts of air-conditioning systems to supply warm air for heating. This definition applies only to an appliance that, for air circulation, depends on a blower not furnished as a part of the furnace.
Energy Commission	California Energy Commission
ELA	Effective Leakage Area
EPA	Environmental Protection Agency
Flue Gases	Products of combustion plus excess air in appliance flues or heat exchangers. This does not include dilution air from a draft diverter.
Gas Vent	A passageway composed of listed factory-built components assembled in accordance with the manufacturer's installation instructions for conveying flue gases from appliances to the outdoors.
GHG	Greenhouse Gas
GRI	Gas Research Institute
GTI	Gas Technology Institute
H	Height of the vent section
HHV	Higher heating value
HRV	Heat Recovery Ventilator
HVAC	Heating, Ventilating, and Air-Conditioning
HVRP	Hot Vent Reversal Pressure
IAQ	Indoor Air Quality
IFGC	International Fuel Gas Code
in.Hg	Inches of mercury
in.w.c.	Inches water column
LBNL	Lawrence Berkeley National Laboratory
Masonry Chimney	A field-constructed chimney of solid masonry units, bricks, stones, listed masonry chimney units, or reinforced Portland cement concrete, lined with suitable chimney flue liners (Note: an exterior masonry chimney is exposed to the outdoors on one or more sides below the roofline).
Metal Chimney	A field-constructed chimney of metal.

NFPA 54	National Fuel Gas Code (National Fire Protection Association Standard 54)
NGAT	Natural Gas Appliance Testing
NO ₂	Nitrogen dioxide
NO _x	Oxides of nitrogen
N _s	Total number of vent sections in the vent connector or common vent
Δp	Pressure differential
Pa	Pascals
P _{nat}	Draft in each vent region
PARR	Partnership for Advanced Residential Retrofit
PG&E	Pacific Gas and Electric Company
PIER	Public Interest Energy Research
PM _{2.5}	Particle matter, with a diameter of 2.5 micrometers or less
ppm	Parts per million
ppmv	Parts per million by volume
RASS	Residential Appliance Saturation Survey
Regulator Vent	The opening in the atmospheric side of the regulator housing permitting the in and out movement of air to compensate for the movement of the regulator diaphragm
RESAVE	Residential Energy Savings from Airtightness and Ventilation Excellence
RESNET	Residential Energy Services Network
Q _f	Mean density of vent gas in the vent section i
Q _i	Mean density of vent gas in vent section i
Q _o	Density of air outside the vent at the elevation of the vent section
RD&D	Research, development, and demonstration
RMS	Root Mean Square
Spillage	Entry of combustion products into a building from dilution air inlets, vent connector joints, induced draft fan case opening, combustion air inlets, or other locations in the combustion or venting system of a vented combustion appliance (boiler, fireplace, furnace, or water heater), caused by backdrafting, vent blockage, or leaks in the venting system.

Type B Gas Vent	A vent for venting gas appliances with draft hoods and other Category I appliances requiring Type B gas vents.
Type B-W Gas Vent	A vent for venting listed wall furnaces.
Type L Gas Vent	A vent for venting appliances requiring Type L vents or appliances requiring Type B gas vents.
Vent	A passageway used to convey flue gases from appliances or their vent connectors to the outdoors.
Vent Connector	The pipe or duct that connects a fuel gas-burning appliance to a vent or chimney.
Vent Gases	Products of combustion from appliance plus excess air, plus dilution air in the venting system above the draft hood or draft regulator.
UCM	Unattended Continuous Monitoring
Venting	The conveyance of combustion products to the outdoors.

REFERENCES

The following references are for the main body of this report only. References for each appendix are listed separately there.

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APPENDIX A:

Assessment of Literature Related to Combustion Appliance Venting Systems

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A1 INTRODUCTION

Concerns about combustion appliance safety are interfering with efforts to improve energy efficiency through residential building retrofits. A key concern is that venting of combustion exhaust from natural draft appliances within the house can be impeded when the house is depressurized, meaning the house has a lower pressure than the outdoors. Since air moves from areas of higher pressure to lower pressure, the depressurization of an inside space relative to the outdoors creates a driving force for air to move from outdoors to indoors through any available opening in the pressure boundary, including the vent of a natural draft – sometimes called an atmospherically vented – combustion appliance. The force of this downward flow is related to the magnitude of depressurization. When depressurization is large in magnitude, the driving flow can overcome the upward (buoyant) force of the hot exhaust gases that drive the normal venting of appliance exhaust. Downward flow occurring when the appliance burner is not operating is called downdrafting. Downdrafting when the burner is operating is called backdrafting. Backdrafting causes the combustion exhaust from the flue to spill into the house. Spillage of exhaust gases containing high levels of pollutants, with carbon monoxide (CO) being the principal concern, presents serious health, and in extreme cases, life-safety hazards. Owing to the potentially catastrophic impacts - including serious illness and death from CO poisoning - the building performance industry promotes extreme caution to avoid backdrafting and spillage from natural draft appliances. CO is not the only pollutant of concern, however: others include nitrogen dioxide, particles, and water vapor.

Downdrafting and backdrafting of combustion appliances are often a result of depressurization. Depressurization of buildings or areas within buildings can occur naturally from wind forces and from flow patterns that result from indoor-outdoor temperature differences. For example, when naturally ventilated buildings are heated in winter, buoyancy causes the higher temperature air to rise and exit through the upper part of the structure. The air exiting through the top creates a negative pressure in the lower part of the building that pulls in replacement air from outdoors (or potentially from the subsurface when the basement is subterranean – a house configuration that is common in some parts of the U.S. but not in California). This process of induced inward flow across a pressure boundary is called infiltration.

Mechanical systems within the house can also cause and contribute to depressurization. Exhaust fans that move air from the interior of the house to outside typically are the most important contributors to depressurization. Air leakage in heating and cooling duct systems can

also contribute to depressurization. Depressurization caused by a fan increases as the amount of air the fan moves increases (roughly to the power 1.5). The largest exhaust fans within houses are typically the clothes dryer and range hood (or other cooking exhaust fan). Clothes dryers connected to lint-free ducts can exhaust as much as 200 cubic feet per minute (cfm). Many range hoods have multiple fan speeds to produce several different flow rates and there is a very large range of maximum flow rates (at the highest speed) for available hoods. Basic range hoods typically have up to a 150 cfm capacity under ideal conditions. Range hoods costing in the range of \$150 to \$350 typically have upper bound airflows of 200 cfm to 300 cfm. Some microwave range hoods can exhaust air in excess of 300 cfm at high speed and “performance” hoods costing in excess of \$400 have the capacity to exhaust more than 500 cfm from the house. Downdraft cooktop exhaust systems are usually designed to deliver in excess of 300 cfm when they have low-resistance exhaust ducts. Bath fans typically are rated for flows of 50 cfm or greater and continuous exhaust fans designed to comply with building ventilation standards typically range from about 40 cfm to 80 cfm. When supply ducts are outside of the pressure boundary (e.g., in the attic or crawl space), leakage from these ducts acts similarly to an exhaust fan.

If the building pressure boundary is very leaky, relatively small pressure differences can produce relatively large infiltration airflows. The pressure boundary for the interior living space may be at the building envelope or at partitions within the shell, depending on construction and any air sealing that has been done. The attic in particular may be included within or be outside the pressure boundary. Sealing large airflow pathways, including large or long cracks and seams in the boundary, reduces the air infiltration that occurs at any specific level of depressurization. Thus, under the same weather conditions and the same indoor-outdoor temperature difference with no exhaust fan use, a more airtight house will have lower infiltration. The pressure vs. airflow relationship also can be driven by mechanical systems. Increasing exhaust flows in a house (with a given level of airtightness) will increase depressurization. If the house has a leaky pressure boundary, much larger mechanically induced airflows are required to produce substantial depressurization. Conversely, if the house is made more air tight, the same amount of exhaust flow will lead to a higher level of depressurization.

Recognizing that the thermal conditioning of infiltrating air can account for a large fraction of annual heating and cooling energy use in residences, air tightening has become a cornerstone of residential energy efficiency retrofit practice and programs. Yet there is also recognition that the increased air tightness and the addition of kitchen, bath, or general exhaust fans will increase the frequency of depressurization that could induce combustion appliance backdrafting and spillage. The response of the low-income weatherization programs and many other retrofit programs targeted at the general public has been to limit air tightening to avoid creating backdrafting hazards. This is the “first, do no harm” principle.

Many tests and other assessment protocols have been developed to identify appliances and houses that present a backdrafting hazard. The two most common test methods for assessing combustion safety are short-term (stress) tests and monitoring. Stress tests, performed under induced conditions, indicate the possibility of backdrafting and capture the effects of outdoor

temperature and wind on venting potential only at the time of the test (i.e., a “snapshot” in time). Additionally, these test methods may produce misleading results: failing houses when backdrafting is not actually problematic or passing houses that may be problematic under some operational conditions. Monitoring, conducted under natural conditions, can capture venting performance over a range of weather conditions, but is time consuming and expensive due to the cost of equipment, equipment set-up and removal, and data analysis. The robustness of monitoring increases with the duration and range of weather and operational conditions during which monitoring occurs, but the cost also increases with deployment time.

As described above, backdrafting and spillage result from a confluence of contributing physical factors that include appliance characteristics and location; vent materials, design, and configuration; air tightness of the building in general and the combustion appliance zone in particular; location-specific weather conditions; characteristics of other mechanical systems in the house; and use patterns of the appliance and other mechanical systems. Since backdrafting and spillage occur only with some confluence or coincidence of physical processes, it is relevant to consider these hazards as having statistical as well as physical characteristics.

Surprisingly, there is no clearly-stated, statistically-rooted risk mitigation target for existing combustion safety diagnostic protocols. Theoretically, the target could be one designed around extreme caution and zero risk (i.e., to identify appliance and venting installations that could backdraft and spill under possible, if highly unlikely combinations of operation and weather). Or the target could be to reduce risk below some level that is considered tolerable (i.e., based on an expected frequency or likelihood of any spillage occurring over the course of a year). Induced stress tests that create nominal “worst case” conditions could be understood as seeking zero risk tolerance. On the other hand, some stress tests and long term monitoring approaches allow (do not treat as failures) short occurrences of transient spillage associated with main burner ignition. Additionally, these tests do not address the health risk associated with allowable spillage. Instead, the depressurization threshold represents the spillage hazard.

Specifying a clear risk mitigation objective is important when trying to assess whether an appliance and venting configuration is problematic, and especially to assess whether a test is effective at finding problematic installations. For the specific objective of no sustained spillage under any circumstance, monitoring would have to be conducted over a long enough period to capture seasonal variations in equipment use and weather. And, the effectiveness of a stress test would need to be assessed against such a long-term monitoring record.

For a no-risk standard, there are two essential questions that are relevant to assessing specific tests.

- (1) Does the test “fail” (or identify as problematic) appliance and venting installations that do not produce sustained backdrafting and spillage in use?
- (2) Does the test “pass” (or not identify as problematic) some appliance and venting installations that actually produce sustained backdrafting and spillage during use?

The former can be characterized as misleading test failures; the latter can be characterized as misleading passes. The concept of a misleading test result is also relevant to probability-based metrics. If the risk mitigation target is, for example, a maximum of three sustained spillage events per year each not lasting more than one hour, then theoretically it would be misleading to characterize as a failure an appliance and venting configuration that spills only once per year.

One approach to overcoming some of the limitations associated with stress tests and monitoring is to use physics-based computer models to simulate the operation of an appliance and other exhaust systems over a typical location-specific weather year. The model must include the physical characteristics of the appliance and vent system (e.g., combustion gas discharge temperature, vent material, pressure losses, and flue type), house air tightness, airflow rates of exhaust devices, heating and cooling system duct leakage, and the configuration of the systems in the house. Also needed are appliance and exhaust system use patterns. In practice, many of these parameters have a probabilistic nature: that is, they vary over time or from house to house. With all of this information and a model that appropriately captures the physical relationships, one could calculate the probable maximum depressurization that would be expected and then predict the occurrence and frequency of sustained backdrafts and spillage. This information would also provide input for defining air tightness, air change rate, and unbalanced ventilation constraints that enable combustion appliances to vent properly while minimizing associated energy penalties.

The objective of this project is to provide the research basis for a more robust method for assessing combustion safety; this literature review is the first critical step. In particular, this report summarizes existing codes and standards for developing venting systems (Chapter 2), combustion safety test methods (Chapter 3), research assessing the combustion safety test methods (Chapter 4), and patents for devices measuring backdrafting and spillage (Chapter 5). Additionally, research on the effects of wind on house depressurization and vent termination are discussed (Chapter 6), because wind can have a significant effect on venting performance and test results. Information on existing simulation software for venting systems is also provided and validation reports, if available, are summarized (Chapter 7). Existing simulation software may provide a useful basis for creating tools that can predict venting performance in combination with other house characteristics. Gaps in existing knowledge that require further research and development are highlighted (Chapter 8).

A2 CODES AND STANDARDS FOR VENT SYSTEMS

Several codes and standards apply to combustion appliances and their vent systems. The National Fuel Gas Code [39] provides information regarding installation and operation of gas appliances in residential buildings. It also provides guidelines for appropriately sizing vent systems and provides a recommended combustion safety test, where a smoke stick or match is used to assess if a combustion appliance is drafting properly. Although the National Fuel Gas Code recognizes that operation of exhaust fans and other appliances can create venting problems for combustion appliances, it does not provide a recommended solution. Other

National Fire Protection Association Codes [40, 41, 42] provide guidelines for designing, constructing, and installing metal and masonry chimneys.

Parts of California's Title 24 Building Code that apply to combustion appliance vent systems [9, 10, 11] quote and reference the information published in the National Fuel Gas Code. The California Residential Compliance Manual [12], however, requires that combustion appliances follow the standards in ASHRAE 62.2.

ASHRAE Standard 62.2 [2] primarily addresses residential house ventilation, but also requires that all combustion and solid-fuel burning appliances must be provided with adequate combustion and ventilation air. For naturally-vented combustion appliances located inside the "pressure boundary" (primary air enclosure separating indoor and outdoor air), the total net exhaust flow of the two largest exhaust fans shall not exceed 15 cfm per 100 ft² of occupiable space when operating at full capacity. If exhaust flow exceeds this limit, then the exhaust fan flow must be reduced or compensating outdoor airflow must be provided. The 2008 Residential Compliance Manual [12] references ASHRAE 62.2 and provides the additional suggestion of moving the combustion appliance outside the pressure zone to solve problems with exhaust flows exceeding the limit.

Further details regarding codes and standards that address combustion appliance safety and vent systems are presented in the following sections.

A2.1 National Fuel Gas Code

The current (2012) National Fuel Gas Code (NFPA 54) [39] lists criteria for the installation and operation of gas piping and gas equipment in residential buildings. The code was originally issued in 1974 (although related efforts began as early as 1913); in 1988, the scope of the code was expanded to include piping systems up to and including 125 psi. In 2002, the code was revised to include requirements for air supplied to combustion appliances and ventilation. The sizing of the gas piping system was also updated. In 2006, expanded steel, copper, and polyethylene pipe sizing tables were included and requirements for appliance shutoff valves were also revised. In 2009, press-connect fittings for gas piping systems were allowed. New requirements for bonding corrugated stainless steel tubing (CSST) piping systems were also incorporated and the sizing table for CSST was expanded. Outdoor decorative appliances and new requirements to seal the annular space around the side-wall vent penetrations were also included. The 2012 edition includes changes on purging fuel gas piping. Additionally, the requirements for bonding of CSST were revised. New requirements for overpressure protection for regulators exceeding 2 psi were added and requirements for "Room larger in comparison with size of appliance" were deleted because changes in boiler and furnace design make this no longer relevant.

NFPA 54 provides installation, design, and sizing guidelines for combustion appliance vents. With the intent of ensuring an adequate supply of combustion air, the code specifies a minimum indoor volume of 50 ft³/1000 Btu/hr (4.8 m³/kW) when the air infiltration rate is not less than 0.40 air changes per hour (ACH). If the air infiltration rate is less than 0.40 ACH, then the required indoor combustion air volume is calculated using equations outlined in Chapter 9

of the code. The code also states that combustion appliances cannot be installed in bedrooms or bathrooms unless the room meets the indoor combustion air volume requirements.

All combustion appliances must be connected to venting systems, except the following: ranges; built-in domestic cooking units listed and marked for optional venting; listed hot plates and laundry stoves; dishwashers; refrigerators; counter appliances; room heaters listed for unvented use; direct gas-fired make-up air heaters; other appliances listed for unvented use and not provided with flue collars; and specialized appliances of limited input such as laboratory burners or gas lights.

The code requires that venting systems satisfy the draft requirements set by the appliance manufacturer. When selecting appropriate vents for combustion appliance venting systems, the code divides combustion appliances into the following four categories: Category I – an appliance that operates with a *non-positive* vent static pressure and with a vent gas temperature that *avoids* excessive condensate production in the vent; Category II – an appliance that operates with a *non-positive* vent static pressure and with a vent gas temperature that *can cause* excessive condensate production in the vent; Category III – an appliance that operates with a *positive* vent static pressure and with a vent gas temperature that *avoids* excessive condensate production in the vent; and Category IV – an appliance that operates with a *positive* vent static pressure and with a vent gas temperature that *can cause* excessive condensate production in the vent. Most residential combustion appliances, including water heaters, furnaces, and ovens, are listed as Category I appliances. Some furnaces with higher exhaust temperatures, however, are listed as Category II appliances.

Most Category I gas-fired appliances use round or oval double-wall Type B gas vents, which generally have an aluminum inner wall and galvanized steel outer wall (Type L vents, which are similar, but have a stainless steel inner wall, can also be used). Vented wall furnaces use an oval-only double-wall Type B-W gas vent. In some cases, the vents pass through a masonry chimney.

Termination points of chimneys for residential or low-heat appliances are required to extend at least 3 feet above the highest point where it passes through the roof and at least 2 feet higher than any portion of the building within a horizontal distance of 10 feet. A chimney for Category II appliances is required to extend at least 10 feet higher than any portion of any building within 25 feet. Masonry chimneys are required to extend at least 5 feet above the highest connected appliance draft hood or flue collar.

Gas vents 12 inches or less in diameter and located at least 8 feet from a vertical wall or similar obstruction are required to terminate above the roof. Gas vents that are over 12 inches in diameter or are located less than 8 feet from a vertical wall or similar obstruction shall terminate not less than 2 feet above the highest point where they pass through the roof and not less than 2 feet above any portion of a building within 10 feet horizontally. A Type B or a Type L gas vent shall terminate at least 5 feet (1.5 m) in vertical height above the highest connected appliance draft hood or flue collar. A Type B-W gas vent shall terminate at least 12 feet in vertical height

above the bottom of the wall furnace. All gas vent terminations must have a vent cap. Further details regarding gas vent termination can be found in Chapter 12.

Tables in Chapter 13 of NFPA 54 provide sizing guidelines for different types of combustion appliances. According to Bohac and Cheple [7], if vents are sized and lined according to tables in Ch. 13 in NFPA 54, then appliances will vent properly. Details for the Bohac and Cheple research can be found in Chapter 3 of this literature review. It should be noted that the minimum allowable vent diameter is 3 inches.

Guidelines for vent connectors when two or more appliances are connected to a single vent are also presented. To ensure proper venting, NFPA 54 requires vents to slope upward at least $\frac{1}{4}$ inch per horizontal foot. Additionally, the connectors shall be attached to the vertical portion of the chimney or vent at an angle of 45 degrees or less relative to the vertical position.

A procedure for performing a safety inspection of existing installed combustion appliances is given in Appendix G of NFPA 54. Surprisingly, the code states that the safety inspection is a recommended but not required procedure. Most of the safety inspection addresses installation of the combustion appliance and checking for gas leaks. One line in the safety inspection addresses combustion spillage and states: "Test for spillage at the draft hood relief opening after five minutes of main burner operation. Use the flame of a match or candle or smoke." The safety inspection recommends that this "test" be repeated when other combustion appliances, located in the CAZ, are operated at full capacity. NFPA 54 recognizes that operation of exhaust fans, ventilation systems, clothes dryers, or fireplaces can create conditions that result in improper venting of a combustion appliance, but it does not provide further instructions for assessing or addressing such situations.

A2.2 International Fuel Gas Code

The current (2012) International Fuel Gas Code (IFGC) [31] establishes minimum regulations for the design and installation of fuel gas systems and gas-fired appliances. The code emphasizes performance of appliances while aspiring to safeguard public health. Although this code is considered independent of NFPA 54 [39], the IFGC provides the same requirements for installing, designing, and sizing vents for combustion appliances as does NFPA 54. One difference between the IFGC and NFPA 54 is that the IFGC does not provide as strict requirements for required volume of indoor combustion air.

A safety inspection for installed gas appliances is recommended in Appendix D of the IFGC. The safety inspection is similar to the inspection published in NFPA 54 [39], but recommends that the procedure be performed prior to modifying the appliance or modifying the existing installation. Additionally, the IFGC states that appliances deemed unsafe for operation should be "shut off." The procedure for making the safety inspection is the same procedure outlined in Appendix G of NFPA 54 [39].

A2.3 NFPA 211

NFPA 211 [40] is a standard for chimneys, fireplaces, vents (for gas appliances), and solid fuel-burning appliances. This standard applies to the design, installation, maintenance, and

inspection of all chimneys, fireplaces, and venting systems. The standard also includes installation, maintenance, and inspection of solid fuel-burning appliances, which is not included in NFPA 54 [39]. NFPA 211 primarily focuses on removal of exhaust gases and the reduction of fire hazards associated with the construction and installation of chimneys fireplaces, and venting systems. This standard recommends using approved engineering methods, such as the vent capacity tables in NFPA 54, manufacturer's instructions, the ASHRAE Handbook: HVAC Systems and Equipment, Ch. 31 [1], and the VENT II (version 4.1 or more current) computer program, when designing vent systems.

In addition to providing the same requirements as NFPA 54 for vent termination and venting material for different types of combustion appliances, NFPA 211 also provides guidelines for chimney selection based on appliance type and flue gas temperature. Further details regarding required caps for vents and chimneys are also provided. For example, the standard states that caps for chimneys or vents shall be designed to prevent the entry of rain, snow, and birds and other animals. If a vent or chimney cap is not listed (published by an organization that meets code requirements, such as UL 441 Standard [52]), then the minimum distance between the underside of the cap and the top of covered flue must be smaller than the width or depth (whichever is smaller) of the covered flue. If more than one flue is covered, then the smaller dimension of the highest flue shall be used.

The standard also requires that screening material attached to the chimney or vent caps to prevent the entry of animals and insects shall not "adversely affect" the chimney or vent draft. NFPA 211 provides more details regarding masonry chimney design and chimney lining, but references NFPA 54 for properly sizing gas vent systems.

A2.4 NFPA 90A

NFPA 90A [41] is a standard for the installation of *air-conditioning and ventilating* systems. This standard specifically covers the construction, installation, operation, and maintenance of systems for air conditioning and ventilation, including filters, ducts, and related equipment, to protect life and property from fire, smoke, and gases resulting from fire or from conditions having manifestations similar to fire. NFPA 90A also lists approved materials for fire proofing ventilation systems and preventing flame spread. It does not provide requirements for properly venting combustion appliances.

A2.5 NFPA 90B

NFPA 90B [42] is a standard for the installation of *warm air heating and air-conditioning* systems. This standard specifically focuses on the construction, installation, operation, and maintenance of systems for warm air heating equipment and air conditioning, including filters, ducts, and related equipment to protect life and property from fire, smoke, and gases resulting from fire or from condition having manifestations similar to fire. NFPA 90B provides detailed instructions for installation of ducts and masonry walls that can also be found in NFPA 211 [40].

A2.6 ANSI/ASHRAE Standard 62.2-2010

ASHRAE 62.2-2010 [2] is a standard for ventilation and acceptable indoor air quality in low-rise residential buildings. The standard lists minimum requirements for mechanical and natural ventilation systems to prevent backdrafting of naturally vented combustion appliances. This standard, however, does not address specific pollutant concentration levels or potential pollutant sources. The standard also does not address unvented combustion space heaters.

Section 6.4 addresses combustion appliances and states that, “Combustion and solid-fuel burning appliances must be provided with adequate combustion and ventilation air and vented in accordance with manufacturers’ installation instructions, NFPA 54/ANSI Z223.1, National Fuel Gas Code, NFPA 31, Standard for the Installation of Oil-Burning Equipment, or NFPA 211, Standard for Chimneys, Fireplaces, Vents, and Solid-Fuel Burning Appliances, or other equivalent code acceptable to the building official. Where atmospherically vented combustion appliances or solid-fuel burning appliances are located inside the pressure boundary, the total net exhaust flow of the two largest exhaust fans (not including a summer cooling fan intended to be operated only when windows or other air inlets are open) shall not exceed 15 cfm/100 ft² (75 Lps/100 m²) of occupiable space when in operation at full capacity. If the designed total net flow exceeds this limit, the net exhaust flow must be reduced by reducing the exhaust flow or providing compensating outdoor airflow. Atmospherically vented combustion appliances do not include direct-vent appliances.”

A2.7 California Residential Code (Title 24, Part 2.5)

The California Residential Code [11] establishes minimum requirements to “safeguard public health”. Most of this document is adapted from the International Fuel Gas Code (2009), but incorporates “necessary California amendments”. The information specific to combustion appliance venting and spillage/backdrafting is the same as that listed in NFPA 54 [39] and the International Fuel Gas Code [31]. The California Residential code adds the requirement that fireplace walls be a minimum of 4 inches thick. The code requires installation of carbon monoxide alarms in addition to smoke detectors in new dwelling units (see section R315).

A2.8 California Mechanical Code (Title 24, Part 4)

The California Mechanical Code [9] is based on the 2009 Uniform Mechanical Code [30] and provides complete requirements for the installation and maintenance of heating, ventilating, cooling, and refrigeration systems. This code has the same standards and requirements for combustion air and ventilation as the National Fuel Gas Code [39]. Chapter 7 of the Uniform Mechanical Code specifically addresses combustion air and ventilation.

A2.9 California Energy Code (Title 24, Part 6)

The California Energy Code [10] describes energy efficiency standards for residential and nonresidential buildings. The purpose of this code is to reduce California’s energy consumption. Requirements related to combustion appliances only address insulation for water-heating systems and equipment.

A2.10 Residential Compliance Manual

The Residential Compliance Manual [12] is intended as an aid to owners, designers, builders, examiners, and energy consultants to comply with and enforce California's energy efficiency standards for low-rise residential buildings. The manual references the California Energy Code (Title 24, Part 6) [10] and ASHRAE Standard 62.2 [2]. With regard to combustion appliances, this manual focuses on defining required appliance energy efficiency. The manual does, however, list the following requirements for combustion appliance venting:

- Combustion and solid-fuel burning appliances must supply combustion and ventilation air from outside according to requirements in ASHRAE Standard 62.2 Section 6.4.
- Combustion appliances must be vented and designed to prevent backdrafting.
- Intermittent ventilation airflow for kitchen range hoods must be a minimum of 100 cfm and intermittent ventilation airflow for the bath fan must be a minimum of 50 cfm (complying with ASHRAE Standard 62.2). However, "care must be taken to avoid backdrafting combustion appliances when large range hoods are used."
- ASHRAE Standard 62.2 includes requirements designed to prevent backdrafting when one or more large exhaust fans are installed within a house containing naturally vented or solid fuel appliances. The requirement states that the net exhaust from the two largest exhaust fans must be less than 15 cfm/100 ft² of floor area with either or both fans operating. If the exhaust fans exceed 15 cfm/100 ft² of floor area, then an electrically interlocked makeup air fan must be installed. This provision applies only when the naturally vented appliance is inside the pressure boundary of the house, and does not include summer cooling fans designed to operate with the windows open. Direct-vent appliances are not considered naturally vented.
- The ASHRAE 62.2 requirement stated above can be solved by moving all naturally vented combustion appliances outside the pressure boundary of the house, reduce the flow rate of one or more of the fans in the pressure boundary, or install a supply fan to balance the exhaust flow. Enclosed areas outside of the pressure boundary can include a vented garage, attic, or closet. Note: the two largest exhaust fans are commonly the kitchen range hood and the clothes dryer. High-end range hoods can have capacities exceeding 1,000 cfm.

A3 GUIDELINES AND TEST METHODS FOR DOWNDRAFTING, BACKDRAFTING, AND SPILLAGE

Over the past twenty-five years, test methods for combustion safety have remained essentially unchanged. In 1988, the Canada Mortgage and Housing Corporation (CMHC) published one of the first guidelines for assessing venting performance of combustion appliances, titled "Procedures for Determining the Safety of Residential Chimneys" [14]. This test requires a visual inspection, a simplified house depressurization test, and a heat exchanger leakage test.

Almost a decade later, the Canadian General Standards Board published CAN/CGSB-51.71, titled “The Spillage Test” (later renamed “The Depressurization Test” in 2005) [13], to determine if air-moving devices (i.e., exhaust fans) in a dwelling impair normal venting of combustion appliances. This test method compares maximum exhaust-fan-induced depressurization of a house with prescribed limits to determine potential for combustion spillage. Around the same time, ASTM (formerly known as the American Society for Testing and Materials) published ASTM-E1998, “Standard Guide for Assessing Depressurization-Induced Backdrafting and Spillage from Vented Combustion Appliances” [3]. ASTM-E1998 references procedures from the CAN/CGSB-51.71 standard and includes four stress test and two monitoring protocols.

CAN/CGSB-51.71 [13] and ASTM-E1998 [3] are the foundation for combustion safety diagnostics currently practiced by residential energy auditing institutions, such as the Building Performance Institution (BPI) and the Residential Energy Services Network (RESNET). Both BPI and RESNET created their own combustion safety standards [5, 46] implementing methods and techniques described in CAN/CGSB-51.71 and ASTM-E1998. However, BPI and RESNET only include induced-depressurization stress test procedures for vented appliances (no monitoring). Additionally, the BPI and RESNET standards require appliance carbon monoxide measurements and do not require or provide recommendations regarding code compliance.

Retrofit companies, weatherization programs, and local utility companies use standards created by BPI and RESNET, but many California programs have recognized the need to include additional safety precautions and code compliance requirements. For example, the PG&E (Pacific Gas & Electric) Combustion Appliance Safety (CAS) test procedure [45], intended for use in the Energy Upgrade California program, includes not only the BPI Combustion Appliance Safety Procedure [3], but also protocols for conducting a visual inspection of the vent system and ensuring proper drafting of cooking appliances and clothes dryers. The CBPCA (California Building Performance Contractors Association) [57] has also built upon the BPI standards by adding a visual safety inspection (e.g., ensuring vents are properly connected, no rust or damage), protocols for unvented appliances (i.e., unvented heaters, stovetops, and ovens), appliance installation code compliance, and combustion ventilation air requirements. The CBPCA guideline contains the most complete protocols for assessing combustion appliance safety and goes beyond concerns related to depressurization-induced backdrafting and spillage.

In this chapter, a detailed summary of each standard and guideline assessing combustion safety is provided.

A3.1 Chimney Safety Tests User’s Manual

The Chimney Safety Test [14] describes a series of procedures for testing the performance of residential chimney systems. The tests are applicable to all standard houses with conventional heating (using gas, oil, or wood) and ventilation systems. The manual presents five test procedures for identifying houses in which spillage of combustion gases into the living area may occur due to a failure of the chimney venting system. The five tests are briefly described below.

1. *Venting System Pre-Test:* This pre-test, not required but recommended, is a visual inspection of the house to determine if it qualifies for the “more rigorous and time-consuming” Venting System Test. Simple measurements (taking 10 to 15 minutes) are used along with reference tables, containing house depressurization limits, to determine if a house is “venting-safe.” The house is depressurized using existing exhaust fans to create a maximum depressurization.
2. *Venting System Test:* This test is designed to ensure that operation of existing household exhaust devices does not adversely affect chimney operation. The impact of fans and fireplace operation on the chimney serving the furnace and/or water heater is tested in addition to the impact of fans and furnace operation on the chimney serving a fireplace. Both the furnace and the fireplace are operated at a maximum level of depressurization to determine if spillage occurs. Spillage lasting more than 30 seconds after the appliance start-up is considered excessive and unacceptable. The test requires 40 to 80 minutes to complete.
3. *Heat Exchanger Leakage Test:* This test provides a quick method for determining if the heat exchanger in an oil or gas forced-air furnace has a major leak. Additionally, the test is a useful diagnostic for determining if the heat exchanger is at fault in a house that experiences spillage. This test is performed after cooling the furnace and then extinguishing the pilot light. Next, exit ports of the combustion chamber are sealed with tape or pieces of foam rubber. Smoke is then placed into the supply air stream (inlet side) of the combustion chamber. Last, while holding the smoke pen near the inlet of the combustion chamber, the circulating blower is turned, pulling the smoke into the combustion chamber. With the circulating blower on, smoke should exhaust out leaks in the combustion chamber, identifying cracks or other leakage areas. Upon completion of the test, the pilot should be relit and the thermostat returned to normal conditions. The guide notes that open flames should not be near the furnace while conducting this test. This test can be completed in 15 minutes.
4. *Chimney Safety Inspection:* This is a visual check for maintenance problems in the chimney system. A checklist is provided as a guide to identify possible repairs and improvements that can improve the performance and safety of the chimney system. This test can be completed in 20 minutes without special equipment.
5. *Chimney Performance Test:* This test is designed to assess if the chimney is capable of providing adequate draft. The temperature of the gases and pressure in the chimney are measured to determine if condensation is a problem or if the draft is low in the chimney. To conduct this test, a window or door must first be partially opened to the outside. Next, the appliance is operated and a timer is started. Temperature and static pressure inside the chimney are recorded after five minutes of appliance operation. Then the appliance is shut off and the windows and/or doors are returned to their original state. The recorded temperature and static pressure values are compared with listed temperature and house depressurization limits, provided in the manual, to evaluate adequacy of the chimney. This test requires 10 minutes to complete.

A3.2 CAN/CGSB-51.71-2005: Depressurization Test

The current CAN/CGSB-51.71-2005 [13] standard is the first revision since its original release in 1995. It provides a test method for determining whether air-moving devices (e.g., exhaust fans) in a dwelling impair normal venting of combustion appliances. The standard specifically states that the “limits are not suitable for predicting non-heating season performance, such as water heater operation during the summer months.” This test method determines fan-induced house depressurization. This depressurization is achieved using exhaust fans and clothes dryers, as well as heat recovery ventilators and the circulating fans of fuel-burning appliances (if their operation results in depressurization). The resultant maximum depressurization is compared to prescribed limits. If the depressurization exceeds the prescribed limit, then the house fails the test and is considered to have a high potential for combustion spillage. The standard notes that wind can greatly affect the accuracy and repeatability of the test and suggests conducting the test on a calm day. The test also states that it does not guarantee that the listed limits will mean an appliance will always vent properly, as weather can have a significant effect.

CAN/CGSB 51.71 -2005 supersedes CGSB 51.71-95. A few of the differences between the versions are listed below:

- The 1995 version was subtitled “The Spillage Test”. The 2005 version is now called “Depressurization Test”.
- Pressure-measuring devices were required to measure from 0 to 25 Pa in the 1995 version, but the range is extended to 0 to 50 Pa in the 2005 version.
- The 1995 standard listed “Interior doors on the perimeter rooms not containing exhaust devices should be closed,” which was removed in the 2005 version.
- In the pre-test checklist, the 1995 standard stated, “Fuel-fired appliances (furnace, boiler, water heater, gas fireplace, pellet stove) should have the thermostats turned down.” The 2005 standard specifies operating conditions for each appliance.
- Air conditioning units were not included in the 1995 standard.
- Continuous pressure limits and intermittent pressure limits were listed separately in the 1995 standard. The 2005 standard groups them together.
- Depressurization limits for the fireplace/wood-burning stove were removed from the 2005 version and a power vent gas appliance depressurization limit was added.

The current test procedure can be summarized as follows. All doors and windows leading outside should be closed. All pressure measuring devices should be calibrated and capable of measuring pressures from 0 to 50 Pa in 1 Pa increments. All exhaust fans and appliances should be turned off (pilot light remaining lit is allowed). Basement doors and doors for an enclosed furnace room should be closed. The test method does not state if other interior doors should be opened or closed to create maximum depressurization. It only states that doors leading to rooms containing exhaust fans or other air-moving devices should be tested to create maximum depressurization in the dwelling space. Each exhaust fan or other air-moving device should be

operated individually and in combination to depressurize the dwelling and measurements are taken in each case. The operating combination that maximizes the depressurization of the house is the one compared to listed values. When wind is present, the standard suggests averaging pressure readings using an electronic manometer with averaging capability or an appropriately sized capillary tube. Depressurization limits for fuel-burning appliances and venting systems are as follows:

Table A1: Depressurization limits for fuel-burning appliances and venting systems from CAN/CGSB-51.71-2005 [13]

Description of Appliance	Max Pressure Limit*
Natural Draft Appliances (includes water heaters, furnaces, and fireplaces)	-5
Sidewall Vented Oil	-5
Pellet Stoves	-15
Sealed Combustion Appliance	-20
Power Vent Gas Appliance	-20

* For infrequently used wood-burning appliances, such as a decorative fireplace, higher depressurization limits may be allowed if they are equipped with warning labels and alarms appropriate for the fuel being burned.

The standard also provides instructions for calibrating pressure measurement devices and suggests taking measurements on a “calm day” to avoid problems associated with wind. A pre-test is available to assess if the dwelling unit requires the depressurization test. It should be noted that this standard does NOT take into account all contributors to depressurization. More specifically, it does not take into account the following:

- Small (<75 L/s) exhaust fans and appliances, such as whole house central vacuum cleaners.
- Powered attic ventilation fans, which may inadvertently draw air from the combustion fuel-burning appliance zone.
- Exhaust caused by a negative pressure in an attached unit of an adjacent dwelling unit, where separation between the units is not complete.
- Exhaust caused by combustion gas venting from fireplaces or wood stoves or other gas or oil-fired appliances that draw air from the dwelling unit.
- Exhaust caused by windows being left open in closable rooms.
- Stack effect, other than that occurring at the time of test.
- Wind, other than effects occurring at the time of test.

- Operation of central circulating fan at higher speed during cooling.
- Intermittent exhaust during the HRV defrost cycle in cold weather.

A3.3 ASTM E1998

ASTM E1998 [3] is a guide that summarizes and compares six common procedures for assessing the potential for, or existence of depressurization-induced backdrafting and spillage from vented residential combustion appliances. For each test method, required equipment, test procedures, and technician and testing times are provided. This standard does not include guidelines for fireplaces and stoves. ASTM E1998 also discusses the advantages and uncertainties of each method. Test procedures are grouped into two primary groups: stress tests under induced conditions and continuous tests (minimum one week of monitoring) under natural conditions. Stress tests under induced conditions can only indicate the possibility of backdrafting due to house depressurization. Test methods under natural conditions detect backdrafting/spillage events that occur during normal use of the house during the test.

ASTM E1998 was first released in 1999. In 2002, the standard was revised to include additional research assessing the six test methods. New referenced documents were also added. The standard was revised again in 2007, to include more referenced documents and update the discussion of methods. The current revision (2011) includes an additional scope that states values are in SI units and other minor corrections.

Stress tests under induced conditions are generally less expensive and time consuming, but failure of the stress tests does not indicate how frequently, if ever, an appliance will spill during normal use. The relationship between weather and stress test results also needs further investigation. Continuous tests are capable of isolating actual backdrafting or spillage events and identifying specific operating conditions and weather conditions that lead to backdrafting and spillage. Continuous tests also can provide an indication of the frequency of events if monitoring is conducted over a sufficient period of time (minimum period of one-week is suggested) and can be scheduled to include weather conditions that are most likely to lead to backdrafting.

To assess whether one week is a sufficient period, it is relevant to consider that backdrafting involves a coincidence of several contributing factors that each vary with time. Outdoor temperature, winds, and operation of exhaust fans and air handlers in combination all may contribute to depressurization of the CAZ. The coincidence of these factors with appliance use may occur in a way that leads to backdrafting at a frequency of less than one week, or only during specific weather or seasonal conditions.

The standard also presents a few results from previous researchers, which suggest that backdrafting and spillage events are rare, and stress tests over-classify houses as spillage prone. Additionally, downdrafting events (without appliance operation) may indicate spillage potential, but it is backdrafting events (during appliance operation) that are associated with spillage. Investigating the impact of weather conditions on the results of tests under induced

depressurization is also recommended. Listed in Table A2 and Table A3 are a summary of the test methods along with limitations of each test

Table A2: ASTM E1998 [3] summary of stress test methods for assessing the potential for, or existence of backdrafting/spillage from vented residential combustion appliances

Name of Test	Directions	Test Limitations	Estimated Test Time
House depressurization with pre-set criteria	Induce worst-case depressurization with both continuous ventilation and intermittent exhaust. Leave combustion appliances <i>off</i> . Measure depressurization, compare to pre-set limits for each appliance type to determine pass/fail for backdrafting and spillage potential.	This test does not assess appliance's ability to overcome house depressurization and does not account for weather variation.	30-40 min
Downdrafting	Induce worst-case depressurization with both continuous ventilation and intermittent exhaust. With combustion appliances <i>off</i> (main burners not firing), use lighter or smoke stick to visually check for downdrafting at the draft hood of each naturally vented combustion appliance to determine pass/fail for spillage potential. Record local weather conditions.	This test does not assess appliance's ability to overcome house depressurization and does not account for weather variation. Suggests testing at low wind speeds.	10-20 min + 15-30 min for vent cooling
Appliance Backdrafting	Induce worst-case depressurization with both continuous ventilation and intermittent exhaust. One at a time, <i>operate</i> (fire main burner) each naturally vented appliance. Use a lighter or smoke stick to visually check for backdrafting at the draft hood. If appliance does not establish a draft within 5 minutes, it fails the test and has spillage potential. Record local weather conditions.	This test does not account for weather variation. Suggests testing at low wind speeds.	20-30 min

Cold Vent Establishment Pressure (CVEP)	Induce worst-case depressurization with both continuous ventilation and intermittent exhaust. Measure and document worst-case depressurization. Turn off ventilation and exhaust. Use blower door to depressurize house. Fire main burner of appliance being tested and visually monitor spillage and backdrafting. Reduce depressurization until appliance begins drafting. Measure and record the depressurization value at which venting is established. This is the cold vent establishment pressure (CVEP). If the worst-case depressurization exceeds the CVEP, the appliance fails the test (and is deemed a risk for spillage).	This test does not account for weather variation. Suggests testing at low wind speeds.	60-90 min
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Table A3: ASTM E1998 [3] summary of continuous test methods for assessing the potential for, or existence of backdrafting/spillage from vented residential combustion appliances

Name of Test	Directions	Test Limitations	Estimated Test Time
Continuous Backdrafting	Monitor and log (using data loggers) the on/off status of main burner for appliance being tested, as well as the vent pressure of that appliance. Document the incidence, duration, and intensity of backdrafting events during monitoring. Minimum duration of one week.	Single week of sampling will capture only limited subset of weather and may miss important coincidences of factors that contribute to depressurization events. Watch for induced draft fans as they can give positive pressures shortly before the furnace fires. Does not measure spillage events.	30-60 minutes + monitoring + 1-2 hours data processing
Continuous Spillage	Monitor and log (using data loggers) the on/off status of main burner for appliance being tested, as well as spillage zone CO and CO ₂	Single week of sampling will capture only limited subset of weather and may miss	30-60 minutes + monitoring + 1-2 hours

	concentrations and temperature to determine the incidence, duration, and intensity of spillage events during monitoring. Minimum duration of one week.	important coincidences of factors that contribute to depressurization events. Spillage temperatures may be misleading due to thermal radiation of appliance.	data processing
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A3.4 BPI Technical Standards for the Building Analyst Professional

The Building Performance Institute (BPI) standards for the Building Analyst Professional [5] provide protocols for performing residential energy efficiency and weatherization retrofit work. In particular, this document provides protocols for evaluating building airflow, building heat loss, and combustion safety. Its purpose is to promote a more uniform (and higher quality) application of house performance and weatherization protocols across the workforce. Upon completing a thorough building analysis, Building Analyst Professionals can provide recommendations for improving performance and maintaining safety of existing houses.

For venting combustion appliances, the BPI document provides three Combustion Safety and Carbon Monoxide Protection protocols. The first protocol is the worst-case depressurization test. This test is conducted by determining the largest CAZ depressurization due to the combined effects of door position, exhaust appliance operation, and air handler fan operation. This test differs from the worst-case depressurization test outlined in ASTM E1998. The test procedure is as follows:

1. *Measure the Base Pressure:* Close all exterior doors, windows, and fireplace damper(s). Set all combustion appliances (boiler, furnace, space-heaters, and water heaters) to pilot setting or turn off the service disconnect. Measure and record the base pressure of the CAZ with respect to outside.
2. *Establish Worst Case:* Turn on the dryer and all exhaust fans. Close interior doors that make the CAZ pressure more negative. Turn on the air handler, if present and leave it on if the pressure in the CAZ becomes more negative, and then recheck the door positions. Measure the net change in pressure from the CAZ to the outside, correcting for the base pressure. Record the worst-case depressurization and compare to the CAZ Depressurization Limits shown in Table A4.
3. *Measure Spillage, Draft, and CO under Natural Conditions:* If spillage occurs under worst case conditions, turn off the appliance, the exhaust fans, open the interior doors, and allow the vent to cool before re-testing. Test for CO, spillage, and draft under natural conditions (described below). Measure the net change in pressure from the worst case to natural in the CAZ to confirm the worst-case depressurization. Repeat for each appliance, allowing the vent to cool between tests.

Table A4: Building Performance Institute [5] combustion appliance zone depressurization limits for natural draft appliances*

Venting Configuration	Pressure Limit (Pa)
Orphan water heater	-2
Boiler or furnace common vented with a water heater	-3
Boiler or furnace with a vent damper common vented with a water heater	-5
Individual boiler, furnace, or domestic hot water heater	-5
Induced draft boiler or furnace common vented with a water heater	-5
Individual induced draft boiler, furnace, or fan-assisted water heater	-15
Chimney-top draft inducer or direct-vented appliance/sealed combustion appliance	-50

* A clarification report [6] is provided in the next section further explaining terminology and depressurization limits.

The second protocol is the Spillage and Draft Test. This test is to be completed for all natural and induced draft space heating systems and water heaters under worst case depressurization and then repeated for natural conditions if the appliance fails worst-case. If multiple appliances share a chimney, appliances should be tested in order of their burner rating (Btu/hr), starting with the appliance with the lowest Btu/hr rating. Induced draft heating systems are checked for spillage at the base of the chimney liner or flue. If a natural draft and induced draft appliance share a chimney (called a common vent), then spillage should be checked at the water heater draft diverter. For natural draft appliances, vent pressure is also measured under steady-state operating conditions 1 to 2 feet downstream of the appliance draft diverter (draft hood). (Note: some technicians drill a small hole through the inner and outer vent walls to insert a static pressure probe and measure pressure; the hole in each wall must be sealed after tests are completed.) Acceptable minimum draft pressures for specified ranges of outside temperatures are listed in Table A5. If spillage occurs upon startup with a cold chimney, then the time it takes for spillage to stop and a positive draft is established should be documented. Appliances that continue to spill beyond 60 seconds after startup fail the spillage test.

The third protocol is the Carbon Monoxide Test. For this test, a worst-case depressurization test is conducted as described in the first protocol. In this test, CO is measured in the flue (as measured, not air-free) of each vented combustion appliance (not in the vent where exhaust gases are diluted after the draft diverter). A probe is placed in the flue and measurements are recorded when the appliance reaches a steady-state operating condition. Holes are not to be drilled in flues for power vented or sealed combustion units. All combustion appliances, except for unvented gas cooking appliances, must be tested for CO under worst-case depressurization conditions and normal draft conditions (if the appliance fails under worse-case conditions). Varying retrofit actions are then prescribed based on the CO measurement results, as summarized in Table A6 for vented appliances (does not include gas ovens). If CAZ

depressurization limits are exceeded under worst-case conditions, then make-up air must be provided or other modifications may be required to bring depressurization to acceptable limits.

Table A5: Building Performance Institute [5] minimum draft requirements based on outdoor temperature

Outside Temperature (°F)	Minimum Draft (Pa)
< 10	-2.5
10-90	$(T_{\text{outdoor}}/40) - 2.75$
> 90	-0.5

Table A6: Building Performance Institute [5] combustion safety test action levels

CO in Flue (ppm)	Draft Test Result Requirement	Action
0-25	Pass	Proceed
26-100	Pass	Recommend CO problem be fixed
26-100	Fails at WC only	Recommend a service call to correct problem
100-400*	see Note	Stop Work
> 400	Passes	Stop Work
> 400	Fails either WC or Nat	Emergency: Shut off fuel to appliance and call for immediate service

WC = Worst-case depressurization; Nat = Natural conditions

*Action required if undiluted, as-measured (not air free) CO reads 100-400 ppm OR the appliance fails under natural conditions

This BPI standard also provides procedures for testing the safety of range tops and ovens. In this test, all items are removed from the oven interior and then the oven is set to the highest setting. CO is measured in the flue, before dilution air. After 5 minutes of operation, CO measurements (as measured, not air-free) are taken. If, at steady state, the oven reads 100 to 300 ppm, then a carbon monoxide detector must be installed. If, at steady state, the oven reads more than 300 ppm, then the unit must be serviced prior to work. If after servicing the oven continues to produce high levels of CO, then exhaust ventilation must be provided with a 25 cfm continuous or 100 cfm intermittent fan.

Inspection of burners on gas stoves, the furnace for flame interference, as well as garage to living space air tightness is also recommended. Analysts are required to carry personal CO monitors during the entire duration of the inspection. If ambient CO levels inside the house exceed 35 ppm, then the analyst is required to abort the inspection.

A3.5 BPI Clarification of CAZ Depressurization Limits

The BPI Clarification Report [6] (2012) clarifies the definitions and the difference between a stand-alone natural draft water heater and an orphaned natural draft water heater. Additionally, it explains that a -2 Pa CAZ depressurization limit was chosen to ensure that negative pressures within the CAZ do not overcome the negative pressures within the vent. Reportedly, “studies” indicate the need for this specific limit. A natural draft water heater vented into an oversized chimney is treated the same as an “orphaned” appliance connected to a common vent that is no longer connected to a furnace. Oversized chimneys include 6 inches or larger square clay lined chimney (8” is most common), 6 inches or larger round B-vent, or 6 inches or larger round Metalbestos vent. A stand-alone naturally drafted water heater, or a water heater vented into a properly sized chimney, is subject to a -5 Pa depressurization limit.

A3.6 RESNET Interim Guidelines for Combustion Appliance Testing and Writing Work Scope

This guide [46] is designed for Residential Energy Services Network (RESNET) accredited Raters and Auditors. It provides guidelines for a gas leakage test, worst-case depressurization test, carbon monoxide (CO) test, and a work scope for each test. The gas leakage test is the same as the one outlined in the BPI standard. The worst-case depressurization test is similar to the BPI standard except the RESNET standard requires installation of a blower door to exhaust 300 cfm if a fireplace is present. The purpose of the blower door is to simulate a fireplace in operation. Depressurization limits are listed in the table below. Guidelines for the CO test procedure are similar to the guidelines in the BPI standard. RESNET recommends “if measured CO levels [in the appliance flue] are higher than 100 ppm (200 ppm for an oven) or an appliance fails to meet manufacturer’s specifications for CO production (whichever is higher), the work scope shall specify replacement or repair of the appliance and the house owner shall be notified of the need for service by a qualified technician.”

Table A7: RESNET [46] combustion appliance zone depressurization limits

Appliance Description	CAZ Pressure Limits
Pellet stoves with exhaust fans and sealed vents	-15 Pa
Atmospheric vented oil or gas system (Category I)	-5 Pa
Oil Power Burner (fan-powered, oil burner); fan-assisted or induced-draft gas; solid-fuel burning appliance other than pellet stove with exhaust fan and sealed vents	-2 Pa

A3.7 PG&E Whole House Combustion Appliance Safety Test Procedure

The PG&E Combustion Appliance Safety (CAS) test procedure [45] is intended for use in the Energy Upgrade California program. This test procedure uses similar methods as the BPI Combustion Appliance Safety Procedure [5] and incorporates the Statewide Low Income

Program Natural Gas Appliance Testing (NGAT) PG&E Low Income Program Weatherization Installation Standards. All combustion appliances within the living space, including cooking appliances and dryers, are tested to ensure proper drafting. This test procedure recommends inspecting combustion appliance vent caps terminating at the roof or exterior walls of the house for signs of soot (although not stated, one must take appropriate fall protection safety precautions, however, when accessing elevated areas). Minimum CAZ depressurization limits and acceptable draft test ranges are the same as those listed in the BPI standard. Listed in Table A8 are conditions in which a combustion appliance will fail the CAS test.

Carbon monoxide (CO) testing procedures are outlined for water heaters, furnaces and gas cook tops, ranges, ovens, and broilers. Gas dryers do not require CO testing. Test procedures for measuring CO in water heaters and furnaces are the same as those listed in the BPI standard. CO limits for each appliance are shown in Table A9. It should be noted that the CO value for the oven/broiler is 226 ppm. For gas cook tops, ranges, ovens, and boilers, the test procedure is as follows:

1. Locate the flue gas termination where applicable.
2. With exhaust fans on, turn on the range burners one at a time, measure and record CO levels 12" above each exposed burner on range tops, cook tops, griddles, and salamanders. Do not expose the sampler tip directly to the flames as false CO readings may occur. A CO level of 26 ppm or higher means the cooktop(s) fails the CAS test. With all cook top burners operating simultaneously, measure the ambient CO at the center of the kitchen and six feet above the floor after one minute of operation. If CO measurements are 10 ppm or higher, the cook top fails the CAS test. (Note: a measurement made one minute after the start of operation may not allow sufficient time for any CO produced at the cooktop to mix throughout the kitchen).
3. Turn the oven temperature to high, and note the time.
4. Run the oven for a minimum of five minutes making sure the burner stays on. Open the door to prevent oven burner cycling. If a separate broiler burner exists (present in all self-cleaning ovens), test the two burners separately, not at the same time. Find the flue gas termination point and take readings for each oven or broiler burner found on the unit. Record the CO for each burner. CO levels of 226 ppm or higher for ovens or broilers fail the CAS test. Measure the ambient CO for operation of each oven, or broiler burner; ambient CO is measured in the center of the kitchen and six feet above the floor after one minute of operation. If the CO measurement is 10 ppm or higher, then the oven or broiler fails the CAS test.

For gas log fireplaces, a CO measurement is taken at least 12 inches above the flame. A CO reading of 26 ppm or higher means the fireplace fails the test. Ceramic logs must be allowed to heat for at least 10 minutes before the test is conducted. A smoke test must be performed to ensure that the appliance is operating correctly. Continuous spillage also means the fireplace fails the test. Dampers must be open during the test. Gas log lighters do not require CO and draft testing.

Table A8: Conditions, outlined by PG&E [45], in which combustion appliances will fail the Combustion Appliance Safety (CAS) test

Combustion Appliance	Description of Failing Conditions
Water Heater	<ul style="list-style-type: none"> • Appliance is located within a sleeping area • Appliance is an open combustion water heater with a standing pilot located in the attic with a whole house fan • Contains a soldered flex connector • Appliance is missing BOTH access doors • Components (e.g., draft diverter, vent) are missing. • Gas is leaking near any of the fittings • The vent pipe is damaged, the draft hood is out of alignment, or spillage is occurring • Excessive rust and weak spots due to corrosion • Contains double draft diverters
Gas Heaters	<ul style="list-style-type: none"> • Contains a soldered flex connector • Appliance is an open combustion water heater with a standing pilot located in the attic with a whole house fan • Appliance is missing flame roll out shield or access door(s) • Components (e.g., draft diverter, vent) are missing. • Gas is leaking near any of the fittings • The vent pipe is damaged or excessive rust and/or weak spots are present due to corrosion
Central Forced Air	<ul style="list-style-type: none"> • Same criteria as Gas Heaters • Return air ducts are damaged
Gas Cook Tops, Ovens, and Broilers	<ul style="list-style-type: none"> • Gas is leaking near any of the fittings
Gas Dryer	<ul style="list-style-type: none"> • Gas is leaking near any of the fittings • Dryer is not properly exhausted to outside the building • Dryer exhaust into another gas appliance vent system • Dwelling has a floor furnace and dryer is exhausted under the house

Table A9: Natural gas appliance testing ambient and flue CO action levels for gas service representative calls (Energy Partners Program, 11-05-0)

Appliance/Room	Ambient CO (ppm)	Measurement Location	Air-Free Flue CO (ppm)
Room	10	Center or home 6 feet above floor	N/A
Floor Furnace	2	Above top of unit	101
Forced Air Furnace	2	Inside supply register	101

		nearest to furnace	
Gas Log Heater	2	Above unit	101
Gravity Furnace	2	Inside supply register nearest to furnace	101
Vented Room Heater	2	Above top of unit and draft diverter	101
Wall Furnace	2	Above top of unit and draft diverter	101
Water Heater	10	Above top of unit	101
Range Top ²	10	Center of kitchen	26 ¹
Oven/Broiler	10	Center of kitchen	226 ¹
Gas Log Fireplace ²	N/A	N/A	26 ¹

NA = Not Applicable

¹ CO is “as measured” NOT “air-free”

² CO measurements should be taken 12 inches above the flame

A3.8 Minnesota Mechanical Systems Field Guide

The Minnesota Mechanical Systems Field Guide [37] provides procedures and information for improving the efficiency of residential heating and cooling systems. This guide provides test procedures for measuring draft in combustion appliances. Test procedures include 1) the smoke test, where the appliance is turned on and a smoke stick or match is used to determine if the appliance is venting properly, and 2) the worst-case draft and pressure test, where pressure inside the vent of the combustion appliance is monitored while exhaust fans are operated and interior doors are open and closed. If the pressure in the vent reaches zero or goes positive, then the appliance is assumed to have a problem. Listed in Table A10 are draft problem solutions. This guide also provides minimum worst-case draft for given outdoor temperatures (see Table A11). The document also provides guidelines for venting material, sizing, and termination and follows the same criteria stated in NFPA 211 [40].

Table A10: Natural draft problems and solutions
(From Table 3-1 in the Minnesota Mechanical Systems Field Guide [37])

Problem	Possible Solution
Draft never established	<ul style="list-style-type: none"> - Check for chimney blockage - Seal chimney air leaks - Provide additional combustion air
Blower activation weakens draft	<ul style="list-style-type: none"> - Seal leaks in furnace and return ducts - Isolate furnace from return registers
Exhaust fan weakens draft	Provide make-up combustion air if opening outside door or window strengthens draft
Closing interior doors during blower door operation weakens draft	Add one of the following: <ul style="list-style-type: none"> - Return ducts - Grills between rooms - Jumper ducts

Table A11: Natural minimum worst-case draft
(From Table 3-2 in the Minnesota Mechanical Systems Field Guide [37])

Appliance	Outdoor Temperature (°F)				
	< 20	21-40	41-60	61-80	> 80
Gas fired furnace, boiler, or water heater	-5 Pa	-4 Pa	-3 Pa	-2 Pa	-1 Pa
Oil-fired furnace, boiler, or water heater	-15 Pa	-13 Pa	-11 Pa	-9 Pa	-7 Pa

A3.9 CBPCA Combustion Appliance Safety Testing Guideline

The California Building Performance Contractors Association (CBPCA) Combustion Appliance Safety Testing Guideline [57] is intended to assist home performance contractors in completing combustion safety tests and incorporates methods from the BPI Combustion Appliance Safety Procedure [5], the Statewide Low Income Program Natural Gas Appliance Testing (NGAT) PG&E Low Income Program Weatherization Installation Standards, and the PG&E Whole House Combustion Safety Test Procedure [45]. The guideline requires indoor ambient CO monitoring for the duration of tests, a visual assessment for combustion hazards, code compliance recommendations, inspection for gas supply leaks, the BPI worst-case depressurization test, a spillage test, CO measurements from all gas appliances (including ovens, cooktops, and dryers), and combustion ventilation air requirements for gas furnaces and water heaters. A summary of each procedure, in order, is as follows:

1. *Indoor ambient CO monitoring:* Turn on the CO monitor outside the house. Enter the house and measure the indoor ambient CO concentration with all exterior doors and windows closed. If the indoor ambient CO level is 10 ppm or greater, then ventilate the house for 15 minutes and check the CO again. If the CO level continues to be 10 ppm or greater, then contact a PG&E service representative. If at any point during the inspection the indoor ambient CO exceeds 35 ppm, abort all diagnostics and inspections. Disable or repair all CO producing appliances before proceeding. The presence of UL-2034 compliant CO monitors is required for all homes.
2. *Visual assessment:* Visually inspect the combustion appliance and combustion appliance zone to identify problems that could result in unsafe conditions (e.g., blockage, air restrictions, leakage, corrosion or other deficiencies). Also, check for problems with the building conditions (e.g., return leak near naturally vented appliances and unvented heating devices, including oven and cooktop used in the living space), the appliance venting (e.g., disconnects and damage), and the combustion appliance location and conditions (e.g., water heater in the bedroom and flame condition of burner – more than

50% yellow). Use of a “Code Check” book is recommended to ensure compliance with current California and local codes.

3. *Gas supply safety:* Examine the entire natural gas or propane line for leaks or unsafe conditions (i.e., uncapped gas lines) and repair as needed. The use of a gas leak detector or soap and bubble solution is recommended for locating gas leaks. Contact a PG&E gas service representative if an aldehyde odor, due to a gas leak, is detected.
4. *Worst case depressurization:* Follow the BPI protocols [5] for worst-case depressurization and ensure that the appliance has adequate combustion air; the volume of the combustion appliance zone is required to be at least 50 ft³ per 1000 BTU/h of combustion appliance capacity operating in that room. Prior to establishing worst case depressurization, measure and record the baseline pressure of the home with respect to outside. While all exhaust fans are operating, excluding whole house fans, position interior doors to maximize house depressurization. The “worst case” depressurization is determined by subtracting the measured baseline pressure from the maximum house depressurization. Compare the measured worst case depressurization with the BPI depressurization limits [5].
5. *Combustion appliance safety testing:* Measure CO in the appliance flue (before dilution) and conduct spillage and draft tests for all natural and induced draft space heating systems and water heaters under worst case depressurization conditions and then natural conditions (i.e., no exhaust fans operating). Test appliances in order of burner capacity starting with the smallest appliance. Inspect flame color and test combustion appliance operation. Measure indoor ambient CO above the appliance and around the draft diverter after the appliance achieves steady-state operation (5 to 15 minutes). Measure CO from unvented cooking appliances and dryers under natural conditions. Unvented heaters are not allowed in the living space. Exhaust ventilation that is ASHRAE 62.2 [2] compliant is recommended for rooms with gas ovens and cooktops. CO action levels are the same as the PG&E combustion safety limits shown in Table A9. Contact a PG&E gas service representative if CO exceeds the limits in Table A9 or if the indoor ambient CO in a supply closet for a furnace is 2 ppm greater than room ambient CO. Conduct the PG&E combustion safety test [45] for the gas oven and cooktop. Ensure that “Air-Free” CO in the exhaust gas from dryers does not exceed 100 ppm.
6. *Combustion ventilation air:* Sufficient combustion ventilation air is required for open-combustion furnaces and water heaters. As stated previously, the volume of the combustion appliance zone must be at least 50 ft³ per 1000 BTU/h of combustion appliance capacity operating in that room. If the total volume is less than this requirement, then it is considered a confined space and action must be taken to increase combustion ventilation air (i.e., transfer grilles or additional room ventilation needs to be added).

A4 PRIOR RESEARCH ASSESSING CODES, STANDARDS, AND GUIDELINES

Extensive research has been conducted in the United States and in Canada to assess the codes, standards, and guidelines in Chapter 3. Much of the literature prior to 1998 [8, 22, 32, 36, 43, 51] assisted in developing ASTM E1998 [3]. Since 1998, research has focused primarily on assessing the repeatability and reliability of standards and guidelines [7, 23, 33, 34, 35, 44]. In particular, research conducted after 1998 broadly has concluded that stress-induced tests are not reliable indicators of spillage potential and are too conservative when predicting spillage (i.e., they predict more spillage than actually occurs). Additionally, the tests do not adequately address water heaters, which are more likely to spill than furnaces (water heaters are more prone to spill in warmer weather). This tendency occurs because the buoyant force that drives airflow is proportional to the temperature difference between the vent gases in the chimney column and the outdoor air. When outdoor air is warmer, the temperature difference and the buoyant force are both reduced. Water heaters are more sensitive to this effect because they generally have smaller burners and thus produce a lower heat flux in their exhaust gases. Also contributing is the reverse stack effect: when indoor temperatures are lower than outdoors, the direction of airflow across the upper building envelope is inward.

For monitoring, researchers have suggested collecting data over longer periods of time to increase test accuracy [23, 35]. Research has also suggested that a house should not be considered as spillage-prone unless it has failed multiple stress-induced tests [23]. Most of the published literature states that continuous tests are more indicative of spillage events than stress-induced tests and if continuous tests are taken for longer periods of time, can better capture effects of weather. In general, houses that met venting design criteria set by the National Fuel Gas Code [39] yield systems with a high probability of venting properly [7].

A summary of the research assessing codes, standards, and guidelines for combustion safety is provided below. This review builds upon a prior review, which focused on literature relevant to residential mechanical system commissioning [55].

A4.1 Flame Roll-Out Study for Gas Fired Water Heaters (1988)

Kao et al. [32] tested five gas-fired water heaters (four natural gas and one liquid propane) in a laboratory with simulated house conditions to evaluate their flame roll-out (flames escaping from the lower part of a water heater) characteristics. They tested the effects of flue blockage, space pressure depressurization, and access door status on flame roll-out. Flame roll-out was identified when temperatures outside the jacket or in the lower part of the water heater exceeded 270°F.

Test results were compared to results from a proposed ANSI test method for testing water heater performance and safety. The authors found that flue blockage, depressurization, and access door status (open/closed) are all major factors in inducing flame roll-out. In conclusion, they made the following recommendations to the U.S. Consumer Product Safety Commission (CPSC) and the ANSI subcommittee on water heaters:

- The final ANSI test method should add a temperature criterion for determining flame roll-out.
- The final ANSI test method should require an interlocking device for access doors to ensure the access door remains closed during heater operation. Additionally, a test method for proper operation of the interlocking device should be included.
- Flue designs should be improved to prevent flow reversal, which causes flame roll out under depressurized conditions.
- Thermal devices should be added to the outside of the water heater and automatically shut off the appliance when temperatures exceed 250°F, indicating flame roll-out.

A4.2 Chimney Venting Performance Study (1988)

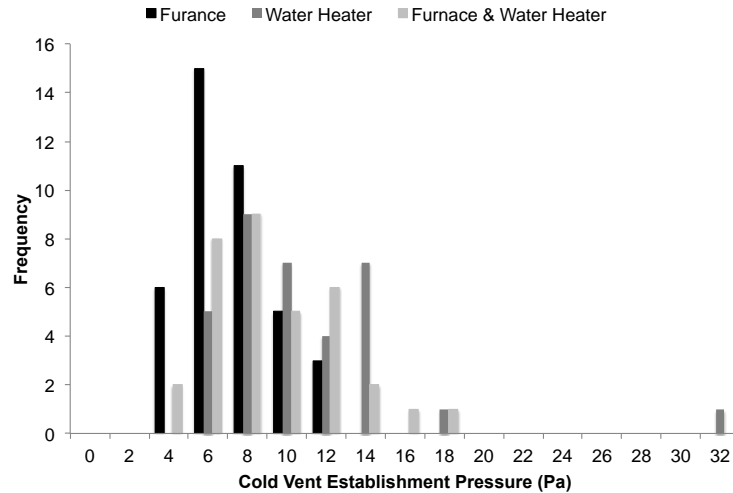
Timusk et al. [51] investigated spillage and backdrafting of 40 houses in the Metropolitan Toronto area by conducting the Cold Vent Establishment Pressure (CVEP) test and the Hot Vent Reversal Pressure (HVRP) test. The HVRP test is similar to the CVEP test, but the appliance is operating and establishes venting before the blower door is used to depressurize the house and reverse the already established upward draft. All houses selected for testing had naturally aspirating gas furnaces and preference was given to houses containing fireplaces (24 of 40 houses). Of the forty houses tested, 36 houses had gas water heaters, which were common vented with the furnace. Wind conditions and outdoor temperatures were measured prior to conducting backdrafting tests. Maximum house depressurization from fireplaces was measured using a “roaring fire” in the fireplace. Maximum house depressurization from exhaust fans was measured when all exhaust fans were operating with all interior doors open. CVEP was measured during furnace operation, water heater operation, and when both appliances were operating simultaneously. The average tightness of the houses tested was 6.4 ACH50 (3.1 ACH50 for the tightest house).

As shown in Figure A1, the average CVEP measured was 6 Pa, while the lowest CVEP measured was 2 to 3 Pa. Of the forty houses tested, eleven had maximum depressurizations greater than 5 Pa, (see Figure A2). For each house, the fireplace accounted for at least half of the depressurization. Figure A3 shows distributions for CVEP, HVRP, and house depressurization due to exhaust fans and fireplaces. The distributions were approximated using a normal distribution with the population mean approximated by the sample mean and the population standard deviation approximated by the sample standard deviation. Their results show that the probability of exhaust fan measurements, without the fireplace, exceeding furnace CVEP measurements is about 3% and about 0.03% for HVRP measurements. Houses with fireplaces were shown to have a higher probability (23%) of depressurizing the house beyond the CVEP limit, as shown in Figure A4(c).

The authors concluded that appliances were able to establish venting in downdrafting chimneys over a range of wind speeds and outdoor temperatures. They found no visible correlation between outdoor temperature and CVEP or wind speed and CVEP. However, results showed that windy conditions assisted in venting combustion appliances. Venting in shorter, one-story,

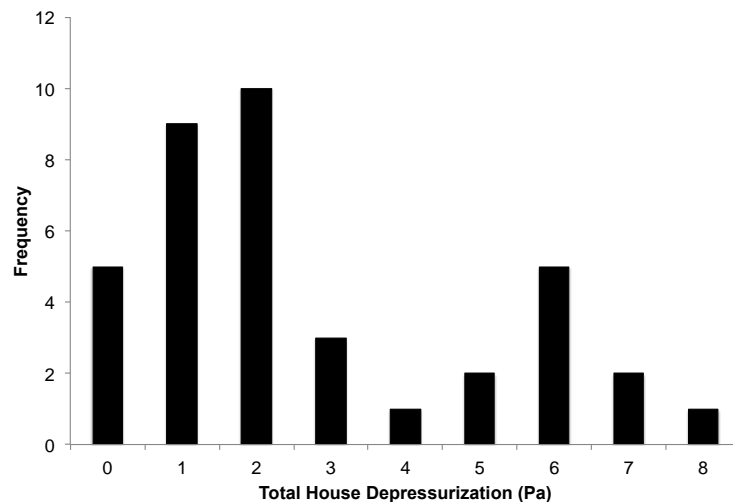
houses was not as reliable as venting in taller, three-story, houses (presumably because of a reduced buoyant force from a shorter column of air in the chimney). Additionally, venting in external chimneys was not as reliable as venting through chimneys that rise within the building envelope (presumably because of a reduced buoyant force from a cooler column of air in the chimney). Techniques developed in this study led to many protocols for the Cold Vent Establishment Pressure test published in the ASTM E1998 [3].

Figure A1: Distribution of CVEP for furnaces, water heaters, and furnaces and water heaters operating simultaneously.



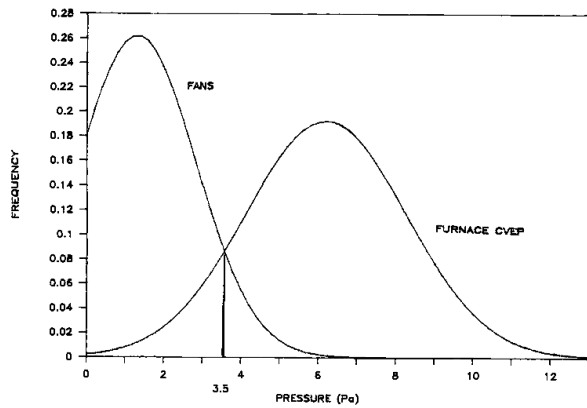
Data were taken from 40 houses located in Toronto (1988) [51].

Figure A2: Distribution of total house depressurization from operation of exhaust-fans and fireplace.

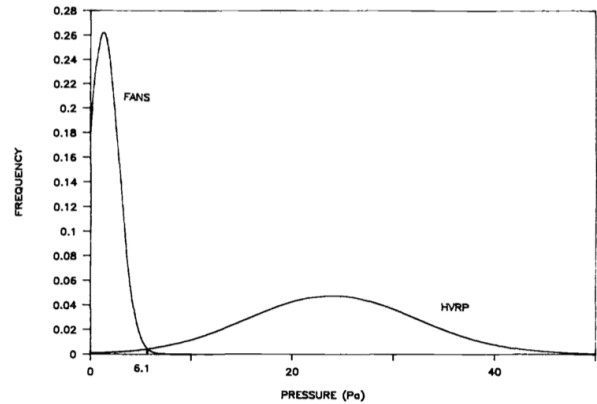


Data were taken from 40 houses located in Toronto (1988) [51].

Figure A3: Normal distributions of furnace CVEP and HVRP tests versus house depressurization from fans and fireplaces.

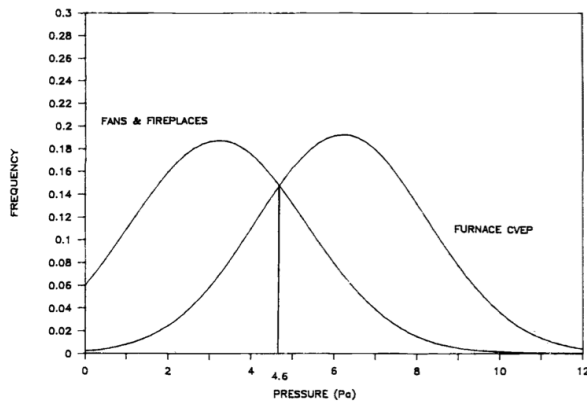


(a) Distribution of furnace CVEP and house depressurization from operating exhaust fans. Mean depressurization from fans = 1.32 Pa, standard deviation = 1.49 Pa, mean furnace CVEP = 6.2 Pa, standard deviation = 2.08 Pa. Probability of one random reading being under both normal curves simultaneously = 3%

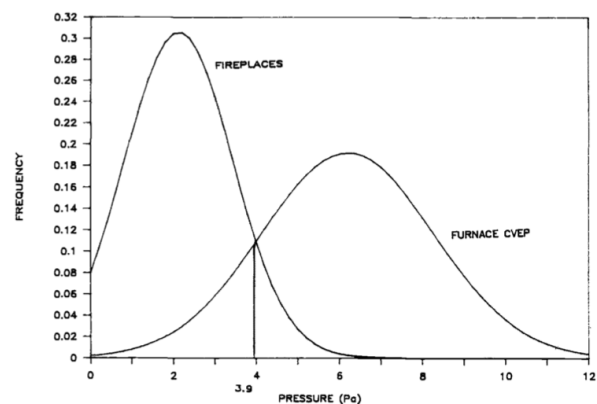


(b) Distribution of furnace HVRP and house depressurization from operating exhaust fans. Mean depressurization from fans = 1.84 Pa, standard deviation = 1.49 Pa, mean furnace HVRP = 23.9 Pa, standard deviation = 8.37 Pa. Probability of one random reading being under both normal curves simultaneously = 0.03%.

Data were taken from 40 houses located in Toronto (1988) [51].



(c) Distribution of furnace CVEP and house depressurization from operating exhaust fans and fireplace. Mean depressurization from fans and fireplace = 3.16 Pa, standard deviation = 2.08 Pa, mean furnace CVEP = 6.2 Pa, standard deviation = 2.08 Pa. Probability of one random reading being under both normal curves simultaneously = 23%.



(d) Distribution of furnace CVEP and house depressurization from fireplace operation. Mean depressurization from fireplace = 2.01 Pa, standard deviation = 1.28 Pa, mean furnace CVEP = 6.2 Pa, standard deviation = 2.08 Pa. Probability of one random reading being under both normal curves simultaneously = 3%.

A4.3 Combustion Safety Checks: How Not to Kill Your Clients (1995)

In this article, which was written for contractors, inspectors, and energy auditors, deKieffer [17] discusses the risk of carbon monoxide (CO), the mechanism of incomplete combustion in naturally vented combustion appliances, and the release of CO as part of the exhaust mixture.

Overall, the article presents a general, qualitative list of safety categories to consider when testing combustion appliances. It also offers advice for organizations wanting to establish their own combustion safety testing standards.

A4.4 Understanding Ventilation: How to Design, Select, and Install Residential Ventilation Systems (1995)

In this book, Bower [8] provides an overview of concerns about and causes of backdrafting and spillage. The author states that backdrafting and spillage are results of house depressurization and combustion appliance venting design. The author also provides suggestions for decreasing the risk of spillage and how to evaluate spillage. The procedure described by the author mimics the worst-case depressurization test outlined in the ASTM E1998 [3]. He also states that the differential pressure in the vent is dependent on the temperature stack effect. Overall, the book provides a good resource for explaining causes of backdrafting and spillage as well as methods for decreasing spillage hazards in houses.

A4.5 Residential Depressurization Protocol Development and Field Study (1995)

Grimsrud et al. [22] developed a working protocol to measure the impact of depressurization on backdrafting and spillage of vented gas combustion appliances. They tested the protocol on nine Minnesota houses and one Chicago house, the GRI Research House, during winter weather conditions. All houses had atmospherically vented furnaces and nine houses had natural draft water heaters common vented with the furnace. One house had a fan assisted furnace common vented with a natural draft water heater. Nine houses had two stories and one house, the GRI Research House, was a single story. All combustion appliances were located in the basement of the house. A summary of house characteristics can be found in Table A12.

Table A12: House characteristics from homes located in Minnesota and Chicago (1995) [22]

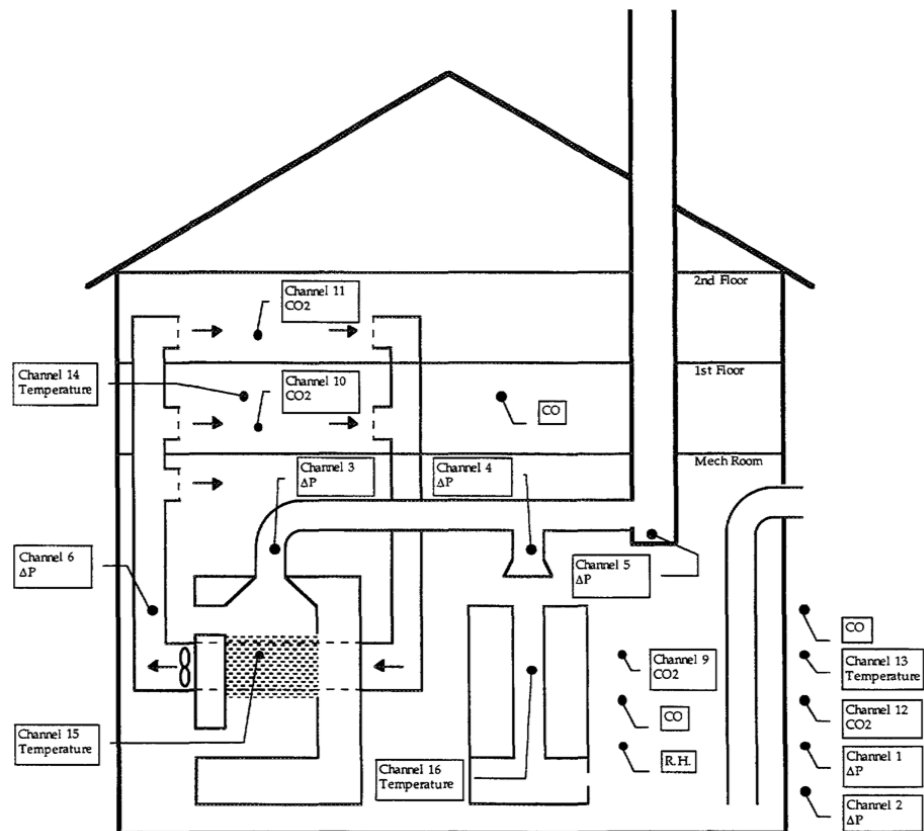
House	Year Built	Area (ft²)	Stories	Furnaces	Water Heaters	CFM 50 (cfm)	ACH 50 (1/hr)
ED1	1952	2460	2	1	1	2440	9.1
EA1	1993	2400	2	1	1	1280	3.3
MI1	1921	5400	2	2 (B)	2	4190	5.8
EP2	1993	3100	2	1	1	1560	3.4
EP1	1993	4750	2	1 (ID)	1	1960	3.1
WO1	1993	3900	2	1	1	1620	2.9
AV1	1994	4900	2	1	1 (E)	1580	2.2
OR1	1992	5250	2	2	1	3860	5.1
WO2	1994	3175	2	1	1	2300	5
CH1	1957	2300	1	1 (ID)	1	3860	12.5

ID – Induced Draft; B – Boiler; E – Electric

The protocol includes a stress test and one week of monitoring of combustion appliances for backdrafting and spillage. The stress test included three major procedures: First, worst-case depressurization in the CAZ was measured by turning on all the exhaust appliances located in the home and leaving all interior doors open. Second, CO in the flue of the appliance was measured in one-minute intervals for five minutes during worst-case depressurization. The author did not state if the reported CO measurements are on an air-free basis. Pressure at the base of the vent was also recorded and used as an indicator for backdrafting. Ambient CO₂ and CO were measured in the CAZ during the duration of the test. Third, if the appliance did not exhibit spillage during the previous test, then a blower door was used to determine depressurization levels leading to spillage, mimicking the CVEP test [3]. Flue CO measurements were also recorded every minute for five minutes during backdrafting induced by the blower door.

For monitoring, CO measurements in the CAZ and differential pressure between the vent and the CAZ were used to indicate backdrafting or spillage. Monitoring was used to verify predictions of the stress test. Figure A4 shows the location of the house measurements and measurements recorded.

Figure A4: Grimsrud et al. [22] house measurements and measurement locations for homes in Minnesota and Chicago



Differential pressure between the CAZ and outdoors (Channel 1) was recorded along with differential pressure between the windward and the leeward side of the house (Channel 2). Exhaust fan appliance status and combustion appliance status was also recorded using temperature and pressure sensors. Indoor air quality was assessed by monitoring CO₂ on each level of the house and measuring ambient CO near other possible sources, such as a gas cooktop in a kitchen or the garage attached to the house. Indoor and outdoor temperatures were also recorded.

Results from the stress test, including outdoor temperature and baseline pressure, are shown in Table A13. Draft columns in Table A13 indicate if the appliance was drafting. A “no” indicates that the appliance spilled during the entire test. A time period indicates the duration after start-up during which the appliance spilled before draft was established. The authors noted that house MI1 had dirty boilers, which could have caused the high CO measurements. Stress tests indicated that four of the ten homes (EP2, EP1, WO1, and AV1) had evidence of backdrafting or spillage in at least one gas appliance.

Table A13: Stress test results from homes located in Minnesota and Chicago (1995) [22]

House	Outdoor Temp (°F)	Baseline Pressure (Pa)	Worst-Case Depressurization (Pa)	Water Heater		Furnace	
				Max Flue CO (ppm)	Draft	Max Flue CO (ppm)	Draft
ED1	15	-4.1	-6.9	5	Y	11	Y
EA1	20	-4	-8.3	130	Y	22	Y
MI1	32	-4	-6.4	<20/ <50	Y/Y	2000/770	Y/Y
EP2	25	-2.2	-7.5	2	N	20	90 sec.
EP1	27	-2.1	-8.9	495	4 min	57	Y
WO1	29	-5.6	-26	26	N	130	N
AV1	45	-2	-9.5	NA	NA	>2000	N
OR1	14	-4.4	-11.3	28	Y	23/29	Y/Y
WO2	23	-5.5	-9.7	4	Y	6	Y
CH1	24	-1.4	-2.9	20	Y	35	Y (fan assist)

One-week of monitoring showed sustained backdrafting events (greater than 1 hr) in three homes (EP2, WO1, and AV1) and high CO levels in one home (AV1). Table A14 shows a summary of the one-week test results. Although the stress test predicted house EP1 having backdrafting problems, the one-week of monitoring showed no evidence of spillage. House EP2 was recorded having three major backdrafting events. The first event lasted 3 hours, the second event lasted 9.5 hours, and the third event lasted 10 hours. House WO1 also had three major backdrafting events, all of which were triggered by the fireplace. House AV1 had the longest duration of backdrafting (12 hrs) and had the highest measured CO in the CAZ and the furnace.

Table A14: One-week, monitoring test results from homes located in Minnesota and Chicago (1995) [22]

House	Extended Backdrafts	Max CAZ CO (ppm)	Max CO source	Max CAZ CO ₂ (ppm)
ED1	None	17	Car Port	940
EA1	None	8	Garage	900
MI1	None	5	Boiler 2	1700
EP2	3	18	Garage	2500
EP1	None	5	Garage	800
WO1	3	11	Garage	2700
AV1	1	> 1000	Furnace	>3000**
OR1	None	near 0	N/A	600
WO2	None	near 0	N/A	800
CH1*	None	> 50	(independent source)	2900

*Artificial introduction of CO and CO₂ using CO source and blower door to induce reverse flow

**3000 ppm is the upper-limit of the CO₂ monitors

Table A15 provides a summary of sustained backdrafting events from houses EP2, WO1, and AV1.

Table A15: Detailed one-week, monitoring test results from homes with extended backdrafting events located in Minnesota (1995) [22]

House	Sustained Backdrafting Event	Trigger of Backdrafting	Duration (hrs)	Max CAZ CO from appliance (ppm)	Max CAZ CO ₂ from appliance (ppm)
EP2	1	Unknown	3	near 0	> 2000
	2	Unknown	9.5	NA	NA
	3	Fireplace	10	NA	NA
WO1	1	Fireplace	3	near 0	2700
	2	Fireplace	4	near 0	2100
	3	Fireplace	4.3	near 0	2500
AV1	1	Range fan, Dryer, and Fireplace	> 12	> 1000	> 2000

The authors concluded that combustion backdrafting and spillage is a pressure problem. The results showed stable, long-term backdrafting in three of the ten houses tested and backdrafting

events persisted even after the triggering event was removed. Elevated levels of CO₂ and water were released during the extended spillage, but carbon monoxide production was minimal in all but one house.

A4.6 The Effect of House Depressurization on the Operation of Gas Appliances (1996)

Aronov et al. [4] investigated the effects of house tightening and house depressurization on the operation of vented gas appliances. All tests were conducted on the American Gas Association (AGA) Research House. The AGA Research House is a 2480 ft² two-story house, with a basement. The house had two bathroom exhaust fans rated at 85 cfm and 120 cfm, and a range hood rated at 200 cfm. Gas appliances (furnaces and water heater) were located in the basement and vented through a 12 inch by 12 inch masonry chimney or a Type B vent, depending on the experiment. Three different types of furnaces were investigated: a fan-assisted furnace with differential pressure proof of flow switch, a fan-assisted furnace with spillage sensor, and a draft hood-equipped furnace with combustion air damper. Two types of water heaters were tested: a draft hood (natural draft) water heater and a water heater with an aftermarket induced draft fan that included a spillage detector mounted around the draft hood. The tightness of the house was around 0.2 ACH at 5 Pa, but could be adjusted by opening or closing ports.

Combustion spillage was measured by injecting a tracer gas, SF₆, into the exhaust stream near the end of the combustion system before the induced draft fan. The amount of tracer gas measured in the living space indicated the amount of spillage from the combustion appliance. For each experiment, tracer gas was only injected into the exhaust stream when the appliance was operating. Tracer gas was sampled in several rooms in the house, including the basement, and in the cold air return ducts. The tracer gas spillage method was validated by inducing 100% spillage and taking samples.

In addition to identifying combustion spillage, backdrafting was indicated using thermocouples installed in the water heater vent connector near the draft hood. Differential pressures throughout the house and across the building envelope were also measured. Temperature measurements were taken in each room of the house, in the basement, and outside the house.

When comparing ACH, depressurization, and building tightness, their results showed that the more the house is depressurized, the higher the ACH rate; however, the leakier the house, the greater the ACH rate for the same level of house depressurization. Their results also showed more air exhausted from the house led to more depressurization, as expected.

To investigate the effects of depressurization on spillage, the authors introduced the “effective depressurization” as a means of normalizing depressurization data and including effects of outside temperature. The effective depressurization is defined as,

$$\Delta p_{\text{eff}} = \Delta p_{\text{dp}} + \left(1 - \frac{T_{\text{air,ref}}}{T_{\text{air}}}\right) h \cdot g, \quad (\text{A1})$$

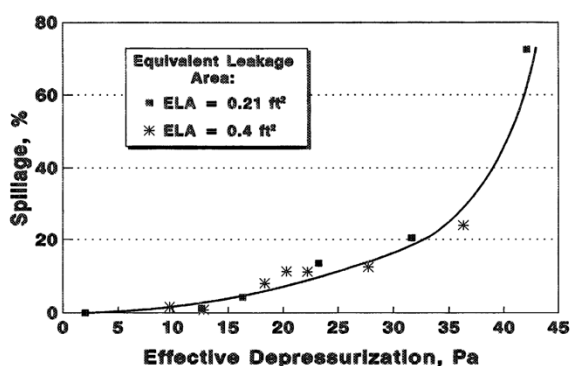
where Δp_{eff} is the house depressurization (differential pressure between indoors and outdoors) in Pa, $T_{\text{air,ref}}$ is the reference outside air temperature in Kelvin, T_{air} is the outside air

temperature in Kelvin, h is the stack height in meters, and g is gravitational acceleration (9.8 m/s^2). The effective depressurization was used in all correlations with spillage, while ACH rate was correlated with pressure drop across the house envelope.

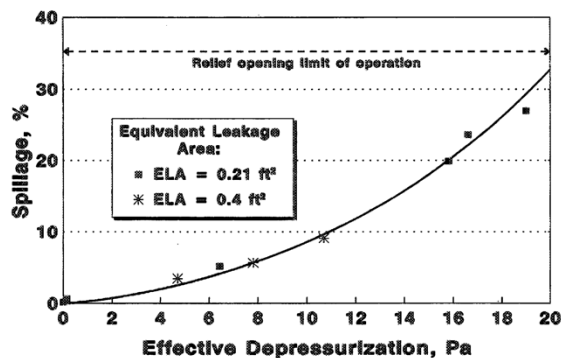
Experimental results showed that spillage is a function of depressurization and is not directly affected by the effective leakage area. Figures A5(a) and A5(b) show a power-law correlation between spillage and effective depressurization for the induced draft furnaces vented alone. For induced draft furnaces common vented with the water heater and for the natural draft furnace vented alone, the power-law correlation only applied to initial depressurization. Then spillage followed a sharp transition to 100% spillage, as shown in Figures A5(c) and A5(d). These correlations were independent of venting system material; however the masonry chimney transitioned to 100% spillage at effective depressurizations around 8 to 9 Pa while the Type B vent transitioned around 13 to 14 Pa (see Figure A6(d)). The natural draft water heater and the induced draft water heater followed the same trends as the natural draft furnace and the induced draft furnace.

The authors conclude that spillage depends on depressurization and is not directly affected by the effective leakage area. For fan assisted appliances and water heaters vented alone, a power-law correlation can be used to relate spillage and effective depressurization. For fan assisted furnaces common vented with a water heater or for natural draft appliances (water heaters and furnaces), spillage initially follows a power-law correlation with effective depressurization, but quickly transitions to 100% spillage as effective depressurization increases. The location of the transition zone depends on the venting system being used. The authors recommend conducting a full field survey to further identify performance patterns.

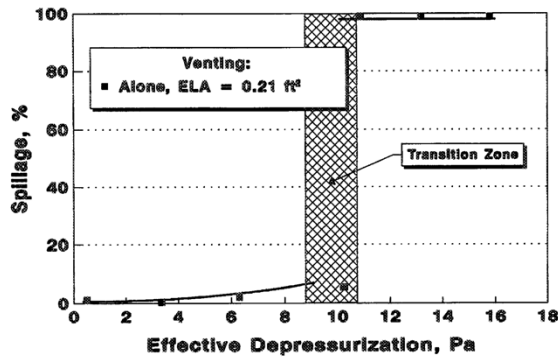
Figure A5: Correlations between spillage and effective depressurization for induced draft and natural draft combustion appliances tested in AGA Research House (1996) [4]



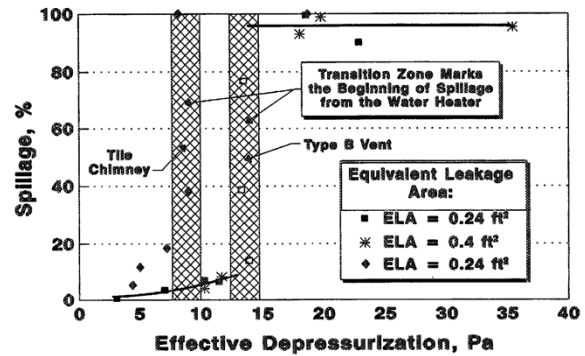
(a) A power-law correlation is shown between spillage and effective depressurization for the induced draft furnace with a pressure switch vented alone using a Type B vent. Spillage came from the vent connector and was not affected by the effective leakage area.



(b) A power-law correlation is shown between spillage and effective depressurization for the induced draft furnace with a relief opening vented alone using a Type B vent. Spillage came from the relief and vent connector and was not affected by the effective leakage area.



(c) For the natural draft furnace vented alone using a Type B vent, a power-law correlation is shown initially between spillage and effective depressurization followed by a transition zone and then 100% spillage regardless of effective depressurization. The transition zone marks an abrupt change to backdrafting.



(d) For the induced draft furnace with pressure switch common vented with a water heater using a Type B vent and tile chimney, a power-law correlation is shown initially between spillage and effective depressurization followed by a transition zone and then 100% spillage.

A4.7 Protocols for Assessing Pressure-Induced Spillage from Gas-Fired Furnaces and Water Heaters (1996)

Koontz et al. [36] initiated a pilot study to develop, test, and refine protocols for assessing pressure-induced spillage from gas-fired furnaces and water heaters. Two main protocols they developed and tested determine spillage potential using a “one-time” (stress) measurement and actual occurrences using monitoring over seven or more days. In this study, protocols were developed from data collected in four stages: 1) House selection and recruitment, 2) initial technician survey, 3) detailed technician investigation, and 4) unattended monitoring. Table A16 provides a summary of the data collection stages and information collected during each stage.

In the first stage of data collection, House Selection and Recruitment, 108 houses in Washington, DC were surveyed. Of the 108 houses, 20 houses were selected to complete the Initial Technician Survey along with the Gas Research Institute’s (GRI) research house located in Chicago, IL (21 houses in total). Six of the houses that completed the Initial Technician Survey (including the GRI research house) were chosen for the Detailed Technician Investigation and tested for backdrafting potential using the stress test methods.

The six houses in the Detailed Technician Investigation were also tested using the Unattended Continuous Monitoring (UCM) for a minimum of one week (7 days). The following measurements were recorded during the UCM: appliance ON/OFF status, fireplace ON/OFF status, temperature in the spillage zone, temperature in two locations in the vent connector, temperature in the common vent, outdoor temperature, temperature in the CAZ, temperature near the thermostat, temperature in the heat exchanger of the appliance, CO in the spillage zone, CO₂ in the spillage zone, CO₂ in the CAZ, relative humidity in the spillage zone, voltage indicating exhaust fan status, NO in the spillage zone (Furnace only), NO₂ in the CAZ, temperature indicating dryer status, differential pressure between the CAZ and outdoors,

differential pressure between the common vent and the mechanical room, and static pressure in the vent connector vs. the CAZ.

Table A16: Koontz et al. (1996) [36] summary of data collection stages and durations for houses in Washington, DC

Data Collection Stage (duration)	Information Collected
House Selection and Recruitment (5-15 minutes for screening questionnaire)	<ul style="list-style-type: none"> • House type and age • House tightness indicators • Furnace and water heater fuel, age location and condition • Other combustion appliances • Exhaust appliances
Initial Technician Survey (1-2 hours)	<ul style="list-style-type: none"> • General dimensions/layout of house • Furnace and water heater fuel, capacity and age/condition • Chimney/flue characteristics • Depressurization measurements • Simple backdraft/spillage test (smoke pencil)
Detailed Technician Investigation (3-4 hours)	<ul style="list-style-type: none"> • House tightness (blower door) • House depressurization potential (exhaust fans) • Neutral pressure level (base pressure) • Cold Vent Establishment Pressure (CVEP) • Hot vent reversal pressure (HVRP)*
Unattended Monitoring (6-8 hours for installation, 7+ days for monitoring)	<ul style="list-style-type: none"> • Furnace and water heater temperatures • Vent and chimney temperatures • House depressurization • Vent and chimney static pressures • Spillage-zone temperatures, relative humidity, and combustion products (CO, CO₂, NO_x) • Status of combustion and exhaust appliances

* The hot vent reversal pressure, or HVRP, refers to the level of house depressurization at which a normally venting combustion appliance starts to backdraft (similar to the CVEP test, but the appliance is operating and establishes venting before the blower door is used to depressurize the house and reverse the already established upward draft).

The results from the stress tests indicated that House 1 had potential for pressure-induced spillage. Both the water heater and the furnace CVEP (3 Pa and 4 Pa, respectively) were below or equal to the measured worst-case depressurization (4 Pa). Table A17 provides a summary of the stress tests for all six houses.

During the one-week of monitoring, House 1 showed spillage events from the water heater and the furnace; however, the spillage events only lasted for 1 to 2 minutes during start-up and coincided with dryer or exhaust fan operation. After 2 minutes of start-up, each appliance vented normally. House 500, the GRI research house, showed spillage during start-up of both appliances, but the authors purposely depressurized the house, causing the appliances to spill.

Table A17: Koontz et al. (1996) [36] summary of stress test results from houses in Washington, DC

House ID	ACH 50 (Pa)	Worst-case depressurization (Pa)	Furnace CVEP (Pa)	Furnace HVRP (Pa)	Water Heater CVEP (Pa)
1	8.9	4.0	4.0	14.0	3.0
16	9.1	3.5	5.0	29.0	3.0
22	11.9	4.4	7.5	15.0	NA
23	8.3	2.3	20.0	27.5	7.5
313	8.2	3.6	9.4	23.0	4.3
500	8.0	2.1	4.0	15.0	3.0

The authors reported emissions measurements for only three of the six houses (including the GRI research house). Tables A18 and A19 provide a summary of emissions measurements in the spillage zone and CAZ, respectively.

Table A18: Summary of maximum spillage zone emissions measurements during one-week monitoring from GRI Research House and selected houses in Washington, DC (1996) [36]

House ID	Appliance	Max CO in spillage zone (ppm)	Duration of Max CO (min)	Max CO ₂ in spillage zone (ppm)	Duration of Max CO ₂ (min)	Max NO in spillage zone (ppm)
1	Furnace	25	1-2	700	1-2	0.55
	Water Heater	19	1-2	2500	1-2	-
16	Furnace	<1	-	600	15	<0.1
	Water Heater	<1	-	450	60	-
500 (GRI House)	Furnace	45	30	2750	5	15
	Water Heater	45	30	750	1-2	-

The authors concluded that tight houses with high potential to depressurize the house with existing exhaust fans have more spillage potential. However, actual spillage events measured using Unattended Monitoring occurred only during appliance start-up (1 to 2 min) and were

rare. Their results show that the most reliable predictor of spillage potential is the ratio of depressurization capability, using continuous and intermittent exhaust fans, to the CVEP, but further investigation is required. For the monitoring, the authors note that temperature alone is not sufficient for indicating actual spillage events and NO and NO₂ readings could be removed from the protocol.

Table A19: Summary of maximum emissions measurements in CAZ during one-week monitoring from GRI Research House and selected houses in Washington, DC (1996) [36]

House ID	Max CO ₂ in CAZ (ppm)	Max NO ₂ in CAZ (ppm)
1	500	<0.1
16	NA	<0.1
500 (GRI House)	NA	0.2

A4.8 Field Protocol for Determining Depressurization-Induced Backdrafting and Spillage from Vented Residential Gas Appliances (1996)

In this report, Grimsrud et al. [25] combined two prior GRI-sponsored pilot studies [22, 36] to develop a common protocol for determining backdrafting and spillage potential in gas appliances. This report provides the field protocol and describes step-by-step procedures for characterizing houses, installing equipment for stress tests and monitoring, measuring house tightness and depressurization levels, and testing backdrafting and spillage potential due to depressurization. The entire protocol can be completed in 4 to 6 hours. No houses were tested in this report. Only a protocol for testing is provided. Table A20 provides a summary of the test methods.

A4.9 Causes and Consequences of Backdrafting of Vented Gas Appliances (1996)

This article, written by Nagda et al. [43], provides a brief review of previous studies investigating depressurization-induced backdrafting and spillage from natural draft combustion appliances. The studies were conducted in Canada, Europe, and the United States. The literature showed that the mean depressurization of houses ranged from -3.0 to -7.6 Pa while the mean CVEP ranged from -6.2 to -9.7 Pa. The mean house tightness was not provided in the article. Many of the studies showed one third of the houses tested had backdrafting problems, but CO measurements were always less than 7 ppm in the living space. In many instances, CO measurements inside the house were lower than CO measurements outside and higher measurements of CO indoors were often caused by unvented appliances or poor burner tune.

The article concludes that causes for house depressurization are well understood, but the frequency and consequences of depressurization-induced spillage are poorly understood, despite the considerable amount of research that has been conducted. The author recommends that future research clearly define the potential problem with naturally vented combustion appliances and that codes and standards be developed to address the problem.

Table A20: Grimsrud et al. (1996) [25] summary of Test Procedures Determining Depressurization-Induced Backdrafting and Spillage

Test Method	Summary of Procedures
Appliance Qualification and Efficiency	<ul style="list-style-type: none"> • Measure ambient CO and CO₂ • Measure combustion products in the flue (CO and CO₂) • Measure efficiency of combustion appliance(s)
Site Characterization	<ul style="list-style-type: none"> • Sketch house exterior and floor plan • Take inventory of appliances • Characterize venting system for water heater and furnace
Installation of Measurement Equipment	<ul style="list-style-type: none"> • Install laptop computer, data acquisition box, and sensors for pressure, temperature, and combustion products • Set system to collect data with 5 second averages during stress tests
House Tightness	<ul style="list-style-type: none"> • Record local weather conditions • Close all doors and windows • Conduct Blower Door test to measure tightness
House Depressurization Level and Backdrafting	<ul style="list-style-type: none"> • Close all doors and windows to outside • Sequentially turn on exhaust equipment and open and close interior doors to achieve maximum depressurization (like BPI test [5]) • Use smoke pencil to assess backdrafting
Cold Vent Establishment Pressure (CVEP)	<ul style="list-style-type: none"> • Use a blower door to substantially depressurize the house • Start appliance • Gradually lower house depressurization until appliance establishes draft • Record depressurization value when draft is established

A4.10 Initial Surveys on Depressurization-Induced Backdrafting and Spillage: Volume I - Washington, DC and Omaha, NE (1999)

Koontz et al. [35] conducted initial surveys in Washington, DC and Omaha, NE to assess the robustness of test procedures outlined in the ASTM E1998 [3]. Four stress tests were conducted: 1) House depressurization test with pre-set criteria, 2) Downdrafting test, 3) Backdrafting test, and 4) Cold Vent Establishment Pressure (CVEP) test. Results from monitoring were used to

determine the reliability of the results from the stress tests. Prior to conducting combustion safety tests, a screening questionnaire, identifying house characteristics, was conducted on 188 households (74 in Washington, DC and 114 in Omaha, NE). After screening 188 houses, 90 houses (53 located in Omaha, NE [23]) were visited by local distribution companies, who provided more information regarding house tightness and venting characteristics. Of the 90 houses visited by local distribution companies, 42 houses were selected for follow-up visits by trained technicians and 16 were visited twice (58 test results total). Houses were visited during the spring. The report does not state how many of the 42 houses were located in Washington, DC and how many were in Omaha, NE. The trained technicians conducted stress tests, installed equipment for monitoring, and provided site characterization. Table A21 provides a summary of tasks completed by trained technicians. A summary of parameters recorded during monitoring is given in Table A22. A total of 42 different water heaters and 34 different furnaces were tested. Sixteen of the water heaters and furnaces were tested twice.

Table A21: Koontz et al. [35] summary of tasks completed by trained technicians for houses in Washington, DC and Omaha [35]

Component	Summary of Associated Procedure
Appliance Qualification Test	Measure background CO and CO ₂ levels in the house, measure furnace/boiler and water heater combustion products in flue.
Site Characterization	Sketch house exterior and each floor, take inventory of gas appliances and exhaust devices, characterize venting system for gas furnace and water heater.
Installation of Measurement Equipment	Install laptop computer, data acquisition box, and sensors for pressures, temperatures and combustion products (CO and CO ₂), program for 1 second averages during stress tests.
Measurements of House Tightness	Note local weather conditions, place house in winter (closed) configuration, use blower door to achieve prescribed depressurization levels, using Energy Conservatory data logger and Blower Door program.
Measurements/Tests of House Depressurization and Backdrafting Potential	Conduct stress tests: (1) house depressurization with preset criteria; (2) downdrafting under natural conditions and worst-case depressurization conditions; (3) backdrafting under natural conditions and worst-case depressurization conditions; and (4) CVEP.
Monitoring	Program data acquisition box for 20 to 30 second averages and instruct occupants to maintain normal practices during the monitoring period (one week). Return after one week to end data collection and remove monitoring equipment. See Table A16 for monitoring parameters.

Table A22: Koontz et al. [35] summary of monitoring parameters for houses in Washington, DC and Omaha

Parameter	Rationale and Measurement Method
Outdoor Temperature	Understand conditions under which any backdrafting or spillage occurred. Measured with a thermocouple placed in a shaded area outdoors near the house.
Indoor Temperature	Understand conditions under which backdrafting or spillage occurred, if any. Measured with thermocouples in the appliance room and living area.
Appliance Status	Confirm that suspected backdrafting events were coincident with appliance operation. Measured with thermocouple in the combustion chamber, taking care not to position too close to pilot light (if any).
Indoor-Outdoor Pressure Differential	Extent of house depressurization, to aid in interpreting potential causes of any recorded backdrafting or spillage events. Outdoor pressure taps were placed on each side of the house, near the center and base of an exterior wall, and connected to a common manifold.
Vent Pressures	A positive vent pressure, measured with reference to the appliance room, indicated times when downdrafting or backdrafting occurred. If the positive pressure was coincident with appliance operation then event is identified as backdrafting with spillage. Pressures were measured in the common vent and each appliance's vent connector, as accessible, or measurement redundancy.
Spillage Temperatures	Thermocouples were placed near appliance draft hoods at locations expected to see higher temperatures during exhaust spillage. Proper positioning to denote spillage was verified during stress tests.
Combustion Products	Investigate the indoor air quality consequences of appliance spillage. Carbon monoxide was measured with two passive electrochemical detectors, one placed in the appliance room and the other placed in the living area. If CO elevations were related to spillage, then the detector in the appliance room should rise first, and to a higher level. CO ₂ was measured with a passive infrared detector placed in the appliance room. Carbon dioxide can be more sensitive to spillage events, because some appliances produce little CO when spilling. Carbon dioxide levels also are affected by the presence of occupants, whereas CO levels are not.

On average, the tightness of the homes was 8.2 ACH50 (16.8 ACH50 maximum and 2.5 ACH50 minimum) and depressurization correlated well with the house's leakage measurement in ACH50. Houses with few to no storm windows had higher leakage than houses with storm windows (about 50% higher ACH50).

Table A23 shows that furnaces generally emitted less CO (air-free) in the combustion chamber than water heaters. The stress tests, summarized in Table A24, suggest that many of the homes tested could have problematic combustion appliances. Houses visited twice did not show repeatable stress test results (see Table A25). All four stress tests were not conducted on all water heaters and furnaces. The downdrafting test and the backdrafting test, under natural conditions, were the only two stress tests conducted on all combustion appliances.

Table A23: Technician air-free carbon monoxide measurements in Furnace and Water heater combustion chambers from 40 houses in Washington, DC and Omaha (1999) [35]

Measurement Location	Air-free CO in Washington Homes (ppm)				Air-free CO in Omaha Homes (ppm)			
	Mean	Median	Max	≥100ppm	Mean	Median	Max	≥100ppm
Furnace								
- 1 st Chamber	6.8	1.0	68	0.0%	5.7	1.0	100	2.0%
- 2 nd Chamber	4.7	0.0	40	0.0%	3.0	1.0	42	0.0%
- 3 rd Chamber	3.3	0.0	30	0.0%	3.2	1.0	42	0.0%
- 4 th Chamber	4.0	1.0	30	0.0%	4.9	1.0	42	0.0%
Water Heater								
- 1 st Chamber	24.0	0.0	290	5.7%	22.5	0.0	998	2.0%
- 2 nd Chamber	6.0	3.0	50	0.0%	1.2	1.0	4	0.0%

Table A24: Summary of stress test results for houses in Washington, DC and Omaha (1999) [35]

Test Method	Percentage (Fraction) of Cases Not Meeting Test Criteria		
	House	Water Heaters	Furnaces
House Depressurization with Preset Criteria	29% (16/56)		
Downdrafting - Natural conditions - Worst case conditions		38% (22/58) 48% (27/56)	30% (15/50) 42% (21/50)
Backdrafting - Natural conditions - Worst case conditions		22% (12/58) 29% (16/56)	8% (4/49) 12% (6/49)
CVEP		38% (22/58)	26% (12/48)

Table A25: Repeatability of stress tests for Washington, DC and Omaha houses visited twice (1999) [35]

Test Method	Percentage (Fraction) of Cases with the Same Test Result		
	House	Water Heaters	Furnaces
House Depressurization with Preset Criteria	73% (11/15)		
Downdrafting - Natural conditions - Worst case conditions		75% (12/16) 81% (13/16)	81% (13/16) 75% (12/16)
Backdrafting - Natural conditions - Worst case conditions		69% (11/16) 69% (11/16)	81% (13/16) 81% (13/16)
CVEP		56% (9/16)	60% (9/15)

The authors also compared results between stress tests and found the following trends:

- Water heaters that failed (did not meet the criteria for) the downdrafting test under natural conditions almost always failed the downdrafting test under worst-case conditions.
- Water heaters that passed (met the criteria for) the downdrafting test under natural conditions almost always passed the backdrafting test under worst-case conditions and the CVEP test.
- Water heaters that failed the backdrafting test under natural conditions failed the backdrafting tests under worst-case conditions and almost always failed the CVEP test.
- Furnaces that failed the downdrafting test under natural conditions almost always failed the downdrafting test under worst-case conditions; similar results were found for the backdrafting test under natural and worst-case conditions.
- Furnaces that passed the downdrafting test under natural conditions passed the backdrafting test under natural conditions and passed the worst-case backdrafting test.
- Furnaces that passed the worst-case downdrafting test also passed the natural and worst-case backdrafting tests
- Furnaces that failed the natural or worst-case backdrafting test, also failed the CVEP test

A summary of these trends including results can be found in Table A26 for water heaters and Table A27 for furnaces.

Table A26: Summary of coincident stress test results for water heaters noted by authors for houses in Washington, DC and Omaha (1999) [35]

Test Method			Downdraft, Worst-Case (Cases)	Backdraft, Natural (Cases)	Backdraft, Worst-case (Cases)	CVEP (Cases)
Downdraft, Natural	Pass	36		Pass (32/34)	Pass (28/29)	Pass (28/29)
	Fail	22	Fail (19/20)			
Downdraft, Worst-Case	Pass	29		Pass (27/28)	Pass (27/28)	Pass (27/28)
	Fail	27				
Backdraft, Natural	Pass	46				
	Fail	12			Fail (10/10)	Fail (10/11)

Table A27: Summary of coincident stress test results for furnaces noted by authors for houses in Washington, DC and Omaha (1999) [35]

Test Method			Downdraft, Worst-Case (Cases)	Backdraft, Natural (Cases)	Backdraft, Worst-case (Cases)	CVEP (Cases)
Downdraft, Natural	Pass	35		Pass (34/34)	Pass (33/34)	
	Fail	15	Fail (14/15)			
Downdraft, Worst-Case	Pass	29		Pass (28/28)	Pass (28/28)	
	Fail	21				
Backdraft, Natural	Pass	45			Pass (41/43)	
	Fail	4			Fail (4/4)	Fail (3/3)
Backdraft, Worst-Case	Pass	43				
	Fail	6				Fail (5/5)

The report also compares house depressurization with outdoor temperature during monitoring. The results showed that houses were slightly more depressurized, on average, during the monitoring than during the trained technician visits. Additionally, houses that were visited

twice showed higher depressurization when the temperature was colder outside. The authors note that the average outdoor temperature during the continuous tests is lower than that for the stress tests, likely because the stress tests were typically performed during daylight hours.

Although the stress tests indicated spillage potential in a significant percentage of the houses tested, there was little to no sustained spillage or backdrafting recorded during monitoring of the houses. The worst-case downdrafting test predicted 40 to 50% of appliances tested had downdrafting potential. The CVEP test predicted 40% of water heaters and 25% of furnaces had backdrafting or spillage potential. The natural and worst-case backdrafting test predicted 25% of water heaters and 10% of furnaces were prone to backdrafting. The repeatability (passing or failing the test consistently) of most stress tests was around 75%. The CVEP test had the poorest repeatability of 60%.

The monitoring results showed that positive pressures measured in vents were most often downdrafting events when the appliance was off or caused by an induced draft fan during appliance start-up. Additionally, CO and CO₂ concentrations showed no spillage during appliance operation, but showed some brief spillage during appliance start-up. Table A28 provides a summary of CO and CO₂ measurements. Durations for the maximum CO and CO₂ measurements were not provided.

Table A28: Summary of CO and CO₂ concentrations from one-week of monitoring houses in Washington, DC and Omaha (1999) [35]

Mean CO in CAZ (ppm)	Mean CO in Living Room (ppm)	Max CO in CAZ (ppm)	Max CO in Living Room (ppm)	Mean CO ₂ in CAZ (ppm)	Mean CO ₂ in Living Room (ppm)
1.5	1.1	8.3	8.7	639	1191

Note: The mean CO and CO₂ were obtained by averaging the data from a single house and then averaging that mean value with all other house mean values. The maximum CO and CO₂ values were obtained by averaging the maximum reading from each home.

In conclusion, the authors recommend extreme caution when interpreting results from stress tests, as the stress tests tend to over-classify houses as spillage-prone. Additionally, the authors state that spillage temperatures are not a reliable indicator of spillage events because thermal radiation from gases flowing near the draft diverter can be mistaken for small amounts of spillage, or vice versa. Monitoring should also be conducted for longer periods of time.

A4.11 Initial Surveys on Depressurization-Induced Backdrafting and Spillage: Volume II - Twin Cities, MN (1999)

In this report, Grimsrud et al. [23] investigated houses in the Twin Cities, MN, continuing the research conducted by Koontz et al. [35]. This study uses the same protocols and procedures as those used by Koontz et al. [35] in Washington, DC and Omaha, NE. Like the previous report, the purpose of this research was to assess the correspondence between the possibility and

occurrence of backdrafting using stress tests and monitoring, as outlined in the ASTM E1998 [3]. A summary of tests conducted and measured parameters for the one-week monitoring can be found in Tables A21 and A22, respectively.

A total of 52 houses in metropolitan Minneapolis/St. Paul, MN were administered screening questionnaires by telephone. From the questionnaire, results showed that most appliances were located in the basements of houses and did not contain vent dampers. Local distribution companies, who provided more information regarding house tightness and venting characteristics, visited 21 of the 52 houses screened. The local distribution companies found that most (~95%) of the houses in Minneapolis/St. Paul and Omaha, NE had proper vent size or pitch. However, only 38% of the houses in Minneapolis/St. Paul had properly sized combustion air supplies. It should be noted that results from the Minneapolis/St. Paul houses are compared with the Omaha, NE houses and the report states that 53 houses in Omaha, NE were visited by local distribution companies.

Of the 21 houses visited by local distribution companies in Minneapolis/St. Paul, 14 were selected for follow-up visits by University of Minnesota field staff. The University of Minnesota field staff also visited an additional 14 houses (28 houses total) not visited by local distribution companies and conducted the protocols outlined in Table A21. Some of the 28 houses were visited twice, but an exact number was not provided. Houses were visited during the late winter and early spring. On average, the tightness of homes was 6.7 ACH50 (3.1 ACH50 minimum and 12.2 ACH50 maximum).

A summary of the stress test results is given in Table A29 and includes houses that were visited twice.

Table A29: Summary of stress test results in Minneapolis-St. Paul houses (1999) [23]

Test Method	Percentage (Fraction) of Cases Not Meeting Test Criteria		
	House	Water Heaters	Furnaces
House Depressurization Test with 5 Pa Criteria	28% (8/29)		
Downdrafting Test - Worst case conditions		38% (11/29)	41% (13/32)
Backdrafting Test - Worst case conditions		27% (8/30)	16% (5/32)
CVEP Test		31% (9/29)	17% (5/29)

The author notes that the CVEP test was affected by wind and that repeat tests in houses showed 20% variation (a high estimate) in results when performed on windy days. The stress test results suggest that many of the homes tested could have problematic combustion appliances. Additionally, appliances that failed the worst-case downdrafting test usually failed

the worst-case backdrafting test and the CVEP test, as shown in Tables A30 and A31. Unlike the homes in Omaha and Washington, D.C., the Minnesota homes showed furnaces emitting slightly more CO (air-free) than water heaters (see Table A32).

Table A30: Summary of noteworthy trends when comparing stress test results for water heaters for houses in Minneapolis-St. Paul (1999) [23]

Test Method		Backdraft, Worst-case (Cases)	CVEP (Cases)
Downdraft, Worst-Case	Pass		
	Fail	Fail (16/17)	Fail (16/17)
Backdraft, Worst-Case	Pass		Pass (8/8)
	Fail		Fail (19/20)

Table A31: Relationship between stress test results for furnaces for houses in Minneapolis-St. Paul (1999) [23]

Test Method		Backdraft, Worst-case (Cases)	CVEP (Cases)
Downdraft, Worst-Case	Pass		
	Fail	Fail (19/19)	Fail (15/16)
Backdraft, Worst-Case	Pass		Pass (3/4)
	Fail		Fail (22/23)

Results from monitoring, conducted for one week, showed that houses were depressurized about the same amount during monitoring and during the field staff visits. Additionally, over half the houses tested showed positive vent pressure at some point during the week of testing, but only a few indicated actual spillage events. Most spillage events occurred for several minutes during appliance start-up or occurred when two appliances, connected to a common vent, were operating at the same time. Table A33 provides a summary of CO and CO₂ measurements. Durations for the maximum CO and CO₂ measurements were not provided.

The authors conclude that stress tests suggested many houses were vulnerable to backdrafting and spillage, but few cases of backdrafting and spillage were actually observed during continuous tests. The authors recommend that stress tests be interpreted with caution,

especially results from the worst-case backdrafting test. Houses that showed positive vent pressures were often downdrafting events (with the combustion appliances off), not backdrafting or spillage events. The authors suggest a house fail multiple (though unspecified number of) stress tests before it is considered spillage-prone. They also recommend that monitoring should take place over longer periods of time (minimum one week) before making any definitive conclusions about the accuracy of stress tests results.

Table A32: Technician air-free carbon monoxide measurements in furnace and water heater combustion chambers from 28 houses in Minnesota (1999) [23]

Measurement Location	Air-free CO in Minneapolis–St. Paul Houses (ppm)			
	Mean	Median	Max	≥100ppm
Furnace				
- 1 st Chamber	11	10	45	0.0%
- 2 nd Chamber	11	10	45	0.0%
- 3 rd Chamber	12	10	45	0.0%
- 4 th Chamber	12	10	45	0.0%
Water Heater	9	5	25	0.0%

Table A33: Summary of CO and CO₂ concentrations from one-week of monitoring from 28 houses in Minnesota (1999) [23]

Mean CO in CAZ (ppm)	Mean CO in Living Room (ppm)	Max CO in CAZ (ppm)	Max CO in Living Room (ppm)	Mean CO ₂ in CAZ (ppm)	Mean CO ₂ in Living Room (ppm)
0.6	1.4	4.5	7.7	682	1355

Note: The mean CO and CO₂ were obtained by averaging the data from a single house and then averaging that mean value with all other house mean values. The maximum CO and CO₂ values were obtained by averaging the maximum reading from each home.

A4.12 Surveys on Depressurization-Induced Backdrafting and Spillage (1999)

In this article, Grimsrud et al. [24] summarized data and results collected in the two GRI reports written in 1999 [23, 35] that assess the relationship between stress tests and one week of monitoring. Stress test and continuous tests, listed in ASTM E1998 [3], were conducted on 181 houses in Washington DC, Omaha, NE, and Minneapolis-St. Paul, MN. The results show that sustained backdrafting events were rare during the monitoring. From this study, stress tests under induced conditions significantly overstated the likelihood of backdrafting and spillage.

Blower door tests were conducted to measure house air-tightness. This study investigated established houses, not new construction. Minneapolis houses were slightly tighter than houses

located in Washington DC and Omaha. Failure rates of stress tests were 30% for downdrafting tests and 40% for backdrafting tests. The majority of failing appliances were water heaters.

Based on results from houses that were visited twice, downdrafting tests had the best repeatability. The strongest correspondence across different types of stress test was between the results of the appliance backdrafting test and the CVEP test for both furnaces and water heaters.

Monitoring was started on the same day that stress tests were conducted to match weather conditions. Outdoor temperatures were between 46 and 40°F. Monitoring rarely showed positive pressures in the vent during appliance operation. Spillage zone temperatures were difficult to interpret because the authors could not distinguish between temperatures showing thermal radiation from heated gases and temperatures showing small amounts of spillage.

Spillage prone houses were monitored additionally with CO and CO₂ monitors. The results show that concentrations of CO and CO₂ increased at startup but elevated concentrations were not sustained. Increases in CO and CO₂ were often attributed to environmental conditions (e.g., unvented appliance, automobiles) instead of the combustion appliance. Water heaters with vent dampers spilled pollutants from the pilot burner (by design) when the main burner was off.

The authors conclude that sustained backdrafting events were rare according to their real-time monitoring results. Additionally, stress tests poorly predicted actual backdrafting events and overstated the occurrence of backdrafting and spillage. Longer monitoring may capture more spillage events. Additionally, the authors suggested that follow-up research should include backdrafting and spillage stress tests and monitoring during hot weather conditions, as this research conducted experiments during winter weather conditions only.

A4.13 Follow-Up Survey on Depressurization-Induced Backdrafting and Spillage in Omaha Residences (2001)

In this report, Koontz et al. [34] conducted a detailed examination of backdrafting and spillage potential by re-visiting a subset of Omaha, NE houses tested in 1999 [35]. Houses were monitored over a period of months, covering multiple seasons to gain a better understanding of characteristics leading to backdrafting or spillage. Houses were selected to provide a range of characteristics and degree of apparent proneness to backdrafting. Results are compared to results collected in 1999 [35].

Stress tests outlined in ASTM E1998 [3] were conducted on nine houses and five of the houses were visited twice. All nine houses tested had venting chimneys located in the middle of the house. A summary of stress tests results is provided in Table A34. CO measurements taken during the CVEP test are provided in Table A35.

The monitoring, lasting two to six months, showed little indication of spillage even on the most “prone to spillage” houses under natural conditions. Nine houses of the 42 originally studied were deemed spillage prone and were monitored for longer periods. In these houses, they performed the following three stress tests: 1) depressurization test, 2) worst-case downdrafting test, and 3) worst-case backdrafting test on houses.

This study is one of the first to primarily focus on how weather conditions affect stress test results. Effects of wind speed on the stress test failure are listed in the Table A36. According to the results, houses were more likely to fail stress tests during low wind speeds (< 1 mph) than high wind speeds (> 8 mph). Table A37 shows the effects of outdoor temperature on stress test failure.

Table A34: Summary of stress test results from nine Omaha houses (2001) [34]

Test Method	Percentage (Fraction) of Cases Not Meeting Test Criteria		
	House	Water Heaters	Furnaces
House Depressurization Test with 5 Pa Criteria	28% (4/14)		
Downdrafting Test - Natural conditions - Worst case conditions		57% (8/14) 64% (9/14)	57% (8/14) 64% (9/14)
Backdrafting Test - Natural conditions - Worst case conditions		36% (5/14) 50% (7/14)	21% (3/14) 21% (3/14)
CVEP Test		57% (8/14)	23% (3/13)

Table A35: Summary of air-free CO concentrations measured during CVEP test from houses in Omaha (2001) [34]

House ID	CO Air-free (ppm)	
	Furnace	Water Heater
N508	625	
N529	580 ¹	
N545	360	
N575		120
N584		110
N588	600	
N602		140
¹ Measured during worst-case backdrafting test		

The relationship between stress test failure and outdoor temperature is somewhat unclear. Houses appear less likely to fail a downdrafting tests in warm weather. However, water heaters were the most spillage prone in warm weather conditions (outdoor temperature > 60°F).

The monitoring showed that positive pressures in the vents usually occurred when the appliance was not operating (downdrafting events). Temperature sensors provided misleading

results for spillage events as the temperature threshold was chosen arbitrarily and could be confused with thermal radiation from the appliance.

Table A36: Outcomes of stress tests (percent “failing”) by wind velocity for houses in Omaha (2001) [34]

Wind Speed (mph)	CGSB Test	Initial Downdrafting Test	Worst-case Downdrafting Test	Water Heater Backdrafting Test	Furnace Backdrafting Test
<1	33% (3)	0% (1)	100% (1)	67% (3)	0% (1)
1-3	37% (24)	30% (20)	45% (20)	33% (24)	20% (20)
4-7	50% (6)	0% (6)	17% (6)	14% (7)	0% (5)
>8	0% (2)	0% (2)	0% (2)	0% (2)	0% (2)

Note: The number of cases on which each percentage is based is shown in parentheses

Table A37: Outcomes of stress tests (percent “failing”) by outdoor temperature for houses in Omaha (2001) [34]

Outdoor Temperature (°F)	CGSB Test	Initial Downdrafting Test	Worst-case Down-drafting Test	Water Heater Backdrafting Test	Furnace Backdrafting Test
20-30	50% (6)	17% (6)	33% (6)	33% (6)	0% (6)
30-40	57% (14)	22% (14)	43% (14)	36% (14)	30% (14)
40-60	28% (7)	14% (7)	28% (7)	0% (7)	0% (6)
>60	0% (8)	0% (2)	0% (1)	44% (9)	0% (2)

Note: The number of cases on which each percentage is based is shown in parentheses

Data from two of the nine houses (N520 and N554) showed highly elevated temperatures, indicating spillage, but both houses were equipped with vent dampers, which “spill” by design when the appliance is not operating. Although spillage did occur in these two houses, the frequency was rare and short in duration (less than 1 minute) during appliance start-up. Table A38 provides a summary of CO and CO₂ measurements taken in the living space for each house.

The authors conclude that stress tests overstate the potential significance of spillage. During the summer months, water heaters were more prone to spillage, but the authors regard this as a minor concern.

Table A38: Summary of CO and CO₂ concentrations measured in the living space from houses in Omaha (2001) [34]

House ID	Mean* CO (ppm)	Max** CO (ppm)	Mean* CO ₂ (ppm)	Max** CO ₂ (ppm)
N501	2.5	6.2	549	492
N505	4.3	7.1	695	1112
N508	0.5	1.9	627	668
N520	2.7	6.0	1206	3075
N529	1.9	2.5	492	750
N545	0.8	1.8	759	855
N554	1.5	2.4	583	1169
N556	4.6	5.8	547	1144
N588	0.8	1.6	633	695

* Mean of weekly averages

** Max weekly average

A4.14 Depressurization-Induced Backdrafting and Spillage: Implications of Results from North American Field Studies (2002)

In this article, Koontz et al. [33] compared field studies, collected between 1980 and 2000, assessing depressurization, backdrafting, and spillage in residential houses located in Canada and the United States. The article specifically compares results from the four depressurization-induced backdrafting and spillage test (stress tests) and the two monitoring outlined in ASTM E1998 [3]. Backdrafting and spillage events indicated by the continuous tests, were considered actual events. After comparing results from previous research, the authors show that stress-induced tests are not reliable indicators of spillage potential and are too conservative when predicting spillage. Continuous test results suggested that many of the stress-induced tests predicted misleading failures (failing houses when backdrafting is not actually problematic). The authors also state that spillage is more likely to occur from water heaters than from furnaces. Additionally, houses in colder climates tend to have tighter envelopes, leading to higher natural and induced depressurization levels that increase the potential for spillage. For monitoring, the authors suggest a minimum monitoring period of one week for predicting spillage potential of a house. They also suggest monitoring the following parameters for continuous tests, as temperature alone does not provide a reliable indication of spillage: pressure in the common vent, CO and CO₂ concentrations in the appliance room, and on/off status of the appliance being monitored.

A4.15 Depressurization-Induced Backdrafting and Spillage: Assessment of Test Methods (2002)

Nagda et al. [44] assessed all the backdrafting and spillage procedures outlined in ASTM E1998-11 using the same data collected by Koontz et al. in 1999 [35]. The data were taken from 42

houses in Washington DC and Omaha, NE. Of the 42 houses, 16 were visited and monitored on two separate occasions, once in the summer or fall and once in the winter. Houses were chosen based on their propensity for backdrafting. On average, selected houses had a base depressurization of 1.9 Pa. Their results showed that none of the houses exhibited any significant backdrafting or spillage, based on monitoring test procedures. All occurrences of positive pressure in the vent or backdrafting were caused by an induced draft fan or were transitional events lasting less than one minute. Stress tests indicated 10 to 40% of study houses might be spillage-prone, while monitoring under real-life conditions showed spillage was rare.

The average baseline depressurization level was -1.9 Pa, with a range from -5.2 to +0.4 Pa. Initial depressurization due to exhaust appliances averaged around -3.4 Pa and ranged from -8.0 to -0.6 Pa. Conducting worst-case depressurization gave a mean value of -4.0 Pa with a range of -14.3 to -0.7 Pa.

The worst-case downdrafting test had the highest failure rate (without appliance operation). When the appliance was operated, the CVEP test had the highest failure rate of all the tests. The water heater did not meet the criterion for appliance backdrafting test about twice as often as for furnaces, suggesting water heaters have greater backdrafting potential than furnaces. Furnaces with induced-draft fans had CVEP values about 50% higher than those without induced-draft fans. Water heaters had a lower CVEP value than furnaces (a lower CVEP value means that the appliance is expected to have a weaker draft or is less able to overcome a downdraft condition).

For monitoring, positive pressure in the vent occurred with induced draft furnaces only during start-up. Water heaters had positive pressure about 1.5 minutes per day, usually during start-up. Most positive pressures measured in vent connectors were downdrafting events (both appliances off).

Houses that were predicted to be more spillage prone were installed with CO and CO₂ monitors. The maximum concentration of CO was 8.3 ppm in the mechanical room and 8.7 ppm in the living room. Most of the houses had CO concentrations below 9 ppm and CO₂ levels below 1000 ppm. Averaging time was 15 seconds, so their results are very conservative (most standards suggest a one-hour average).

The author's concluded that monitoring of pressures in the common vent showed no instances of sustained backdrafting. Positive pressure measurements inside the vent were usually due to start-up of the induced-draft fan furnace. Water heaters have greater backdrafting potential than furnaces. Average indoor-air concentrations of CO were low. Stress tests did not always agree with continuous tests. The authors are uncertain of the credibility of the stress tests. They believe continuous tests are more indicative of spillage events and that stress tests are misleading. Their results indicate that the collection of indicators provides a better indication of backdrafting than does any one indicator. Note: weather conditions (wind speed or air temperature) and house leakage data were not provided.

A4.16 Ventilation and Depressurization Information for Houses Undergoing Remodeling (2002)

In this report, Bohac et al. [7] investigated the ventilation of houses tightened by the Sound Insulation Program (SIP) for the Minnesota Department of Commerce. Houses near the Minneapolis-St. Paul International Airport were acoustically treated to reduce the interior sound level by 5 dBA. Depending on the house, treatment could include new windows, storm doors, roof vent baffles, wall insulation, attic insulation, chimney vent caps, air sealing, air conditioning, and replacement furnace. Due to the large number of houses tested, venting during a variety of seasons was captured. If venting of an appliance failed during the summer months, then the house was re-tested at the beginning of the heating season.

Houses in Minneapolis-St. Paul were tested both before and after the SIP treatment, but combustion spillage data for vented appliances is only reported for tests conducted *before* the SIP treatment. Flue Carbon Monoxide (CO) test results are reported for both before and after the SIP treatment for ovens. A summary of the methods used for assessing combustion safety can be found in Table A39.

Table A40 provides the depressurization limit guideline for the worst-case depressurization test. For the flue carbon monoxide test, 3% of natural draft water heaters and 8% of the furnaces failed the CO standard of 100 ppm. The furnace failure rate almost doubled when the test was performed under downdraft conditions (see Table A41). CO measurements in the flue were “as measured” and not adjusted for excess combustion air (air-free). A distribution of CO measurements for each appliance can be found in Table A42.

Table A39: Bohac et al. (2002) [7] summary of methods used for assessing combustion safety of houses in Minneapolis-St. Paul

Test Name	Measurements Recorded	Test Requirements	Appliances Tested
Flue Carbon Monoxide	<ul style="list-style-type: none"> Carbon monoxide measured after 5 minutes of burner operation 	<ul style="list-style-type: none"> CO < 150 ppm for ovens/ranges CO < 100 ppm for vented appliances 	<ul style="list-style-type: none"> Ovens Water Heaters Boilers Furnaces
BPI Worst-Case (WC) Depressurization	<ul style="list-style-type: none"> Pressure differential between CAZ and outside 	See Table A21	<ul style="list-style-type: none"> Water Heaters Boilers Furnaces
Combustion Vent Spillage	<ul style="list-style-type: none"> Draft (using smoke) Temperature at three locations around draft hood 	<ul style="list-style-type: none"> Conduct test at WC depressurization and Natural Conditions No spillage after 1 min for furnaces No spillage after 3 min for 	<ul style="list-style-type: none"> Water Heaters Boilers Furnaces

		water heaters and boilers • Spillage occurs when average temperature difference between draft hood and CAZ > 44°F or temperature difference between one draft hood sensor and CAZ > 55°F	
Combustion Vent System Design	• Vent system construction (size, vent type, vent connectors, elbows, etc.)	See vent capacity tables in National Fuel Gas Code [39]	• Water Heaters • Boilers • Furnaces

Table A40: Bohac et al. (2002) [7] depressurization limit guideline for houses in Minneapolis-St. Paul

Appliance Type	Depressurization Limit (Pa)
Individual (orphan) water heater (WH)	-2
Natural draft WH and furnace or boiler	-3
Induced draft furnace/boiler & natural draft WH	-5
Individual natural draft furnace or boiler	-5
Individual induced draft furnace or boiler	-15
Common vent with chimney-top draft inducer	-15
Power vented and sealed combustion	>25

Table A41: Summary of results for flue carbon monoxide test for houses in Minneapolis-St. Paul (2002) [7]

Appliance	Total Tested	Percent Failed Test
Oven	2,891	25% (before treatment) 7% (after treatment)
Water Heater (when venting)	1,356	3%
Water Heater (during DD*)	1,356	5%
Furnace (when venting)	548	8%
Furnace (during DD*)	548	14%

* DD indicates that the test was conducted while down drafting was induced

Table A42: Distribution of natural gas appliance carbon monoxide measurements for houses in Minneapolis-St. Paul (2002) [7]

Range (ppm)	Oven			Water Heater		Natural Draft Furnace	
	2 min	5 min	Steady	Normal	DD	Normal	DD
<= 25	4%	15%	27%	90%	88%	85%	78%
25-50	4%	21%	27%	5%	5%	5%	5%
50-100	10%	26%	23%	1%	2%	2%	2%
100-150	9%	13%	10%	0%	1%	2%	2%
150-250	17%	12%	7%	1%	1%	1%	2%
250-500	28%	9%	4%	1%	1%	1%	2%
> 500	28%	4%	2%	2%	2%	4%	7%

* Measurements conducted when the appliances are venting properly

** Measurements conducted while a down-draft was induced

The worst-case (WC) depressurization test was conducted on 1,427 houses. Houses were selected based spillage potential. The WC depressurization test was used as a design guideline to predict the likelihood of a depressurization problem after a house has been tightened and exhaust ventilation added. To compensate for fluctuations in pressure reading during windy conditions, a computer was used to estimate WC depressurization using exhaust fan flow rate and measured depressurization. The authors note that orphaned water heaters proved to be the most susceptible to depressurization induced combustion spillage problems, as 36% failed the WC depressurization test. Other appliances proved to be less problematic, as shown in Table A43. It should be noted that these results do not necessarily imply that orphaned water heaters are more susceptible to spillage; instead, orphaned water heaters are more likely to fail worst-case depressurization because they have the lowest threshold.

Table A43: Summary of results for worst-case depressurization test for houses in Minneapolis-St. Paul (2002) [7]

Appliance Type	Depressurization Limit	Percent Failed Test*
Individual (Orphan) water heater (WH)	2	36%
Natural draft WH and furnace/boiler	3	12%
Induced draft furnace/boiler & natural draft WH	5	5%
Individual natural draft furnace/boiler	5	5%
Individual induced draft furnace/boiler	15	0%
Common vent with draft inducer	15	0%
Power vented and sealed combustion	>25	0%

* Percentage of houses with measured depressurization greater than the listed limit

The combustion spillage test was conducted on 1,303 natural draft water heaters and 554 natural draft furnaces under worst-case depressurization conditions and natural conditions. As shown in Table A44, 11% of natural draft water heaters and 4% of furnaces fail the spillage test under worst-case and natural conditions. These spillage failure results are consistent with those reported by Nagda et al. [44], showing almost twice as many water heaters fail than furnaces.

Further analysis was conducted to examine how the venting system design of water heaters affected combustion spillage. The results show that 25% of water heaters with transite (asbestos insulated) liners failed, while 12% to 14% of water heaters with tile and exterior tile failed (see Table A45).

The impact of vent connector size on combustion spillage was also investigated. The results showed that connectors undersized up to 40% had an average failure rate under natural conditions of only 10%. Connectors undersized by more than 40% had a failure rate of 31%. The author suggests that venting systems designed to meet the requirements in the National Fuel Gas Code (NFGC) tables have a high likelihood of venting properly, but systems that are undersized are not guaranteed to fail.

Table A44: Combustion spillage test results for houses in Minneapolis-St. Paul (2002) [7]

	Natural Draft Water Heater	Natural Draft Furnace
Percent Passed Both WC and Nat.*	81%	90%
Percent Failed WC and Passed Nat.	9%	6%
Percent Failed Both WC and Nat.	11%	4%

* "Nat." implies the test was conducted under natural conditions.

Table A45: Water heater spillage test results by chimney type for houses in Minneapolis-St. Paul (2002) [7]

Chimney Type	Pass Both	Fail WC Pass Nat.*	Fail Both
Interior Tile	75%	11%	14%
Exterior Tile	81%	7%	12%
B-vent	83%	10%	6%
Transite	71%	4%	25%
Interior Tile with Metal Liner	86%	7%	7%
Exterior Tile with Metal Liner	78%	9%	13%

* "Nat." implies the test was conducted under natural conditions.

The following conclusions are made in this report:

- Combustion venting systems that meet the design guidance in the National Fuel Gas Code tables [39] have a high probability of venting properly.
- Depressurization for common vent water heaters should be no more than 5 Pa. A depressurization limit of 3 Pa can be set for a 5 to 20% failure rate for all outdoor conditions.
- Monthly tracking of spillage failure suggests that spillage failures are more frequent during warmer outdoor conditions. Results show spillage failure drops significantly when the outdoor temperature is less than 40°F.
- Appliances that fail under natural conditions are likely to spill under most conditions.
- A standard “clean and tune” maintenance of a furnace can reduce elevated CO under downdraft conditions.
- The downdrafting test may be an indication of water heaters starting to go “out of tune,” but this theory has not been verified.

A4.17 Residential Combustion Spillage Monitoring (2004)

Fugler [19] presented a research highlight about combustion spillage research that was conducted for the Canada Mortgage and Housing Corporation, which was first published in 1987, but never released. The purpose of this study was to perform more detailed monitoring on houses that experienced combustion spillage. Monitoring activities were performed on 16 houses and carried out over a period of 14 to 35 days. A data acquisition system recorded appliance status (on/off), occurrence of spillage, if windows and doors were open, if exhaust fans were operating, and if the fireplace was in use. Thermistors were used to determine combustion appliance status and indicate spillage.

Houses that showed significant spillage (10 seconds of spillage for gas-heated house and 5 seconds for an oil-heated house) were further investigated to determine the effects of spillage on indoor air quality. Houses that were forced to spill gave high readings of CO₂ and sulfur dioxide (SO₂); however, houses with naturally occurring spillage had levels that would not be considered hazardous.

Overall, the results indicate that combinations of environmental and house operation characteristics most conducive to combustion spillage are rare. Appliance and venting system configuration have a stronger correlation with spillage events than effects of outside temperature and wind. Poor chimney performance is likely the largest contributing factor to combustion spillage. The authors suggest emphasis be placed on improving chimney performance to prevent combustion spillage.

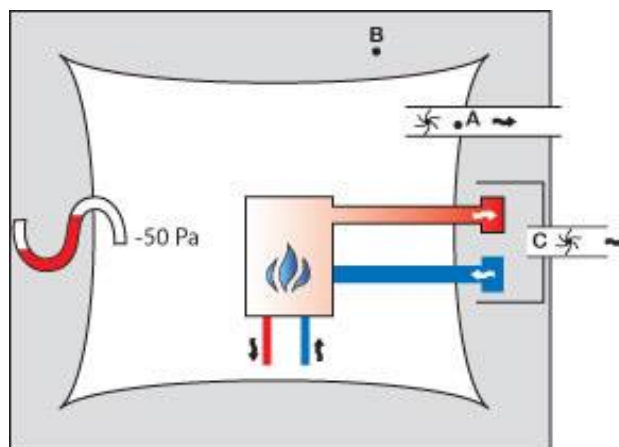
A4.18 Development and Evaluation of a New Depressurization Spillage Test for Residential Gas-Fired Combustion Appliances (2005)

This report [15] describes the development of a new depressurization test for combustion appliance manufacturers and certification agencies to differentiate products in terms of spillage

resistance. The test is also designed to help manufacturers develop and market more spillage-resistant combustion appliances. To develop the new depressurization test, the performance of seven residential combustion appliances was evaluated in a Canadian commercial testing laboratory. The following appliances were tested: two power-vented, storage-tank water heaters; one code-compliant, “mid-efficiency”, natural draft furnace; two high efficiency condensing furnaces; and two direct-vent gas fireplaces.

The concept of the depressurization spillage test is shown in Figure A6. The box with a flame represents a combustion appliance installed in the depressurized test room. The horizontal ducts colored red and blue represent the combustion air inlet and combustion gas vent. A direct vent combustion appliance is shown in Figure A6, but not all appliances tested were direct vent appliances. The fan installed in duct “A” was used to depressurize the room and discharged outside the building. A supplemental exhaust system, located at “C”, captured and removed combustion products to avoid contaminating the area adjacent to the room, location “B”.

**Figure A6: Simplified concept of depressurization spillage test
taken from the report [15]**



The test used CO₂, produced in the combustion process, as a tracer gas, to determine spillage. The amount of combustion spillage was determined by dividing the amount of CO₂ released into the test room from the appliance and its combustion venting system during the test cycle by the amount of CO₂ produced by combustion of the fuel that was consumed during the test. The ratio of the two provides a direct measure of the combustion spillage of the appliance and its venting system during each test in percent. For natural gas, the same CO₂ production factor was used in all calculations. They calculated both volumetric and unit energy CO₂ production factors.

Each unit was initially tested at 50 Pa depressurization. If combustion spillage of the unit exceeded 2% (CO₂ measured from spillage in test room divided by CO₂ fuel-predicted), then the test was repeated at 20 Pa depressurization. If the measured spillage exceeded 2% at 20 Pa, a final test was performed at 5 Pa depressurization.

Appliances were operated for a five minute period of burner operation with the room depressurization level controlled at the selected value. The burner fuel consumption, the concentration of CO₂ in the test room, and the exhaust fan flow rate were monitored throughout the five minute combustion period. Measurements were continued for two minutes immediately following the burner shutoff to capture transient combustion products.

The depressurization test protocol can be summarized as follows:

- Prepare the appliance by operating it for at least four hours to allow removal of manufacturing residues.
- Adjust the pressure inside the test room to the desired depressurization level.
- Position the CO₂ monitor inside the test room between 0.5 and 1m from the appliance burner.
- Operate the appliance at its maximum firing rate.
- Measure and record the CO₂ levels in the test room, the test room depressurization, and the appliance fuel consumption rate every 30 seconds for a total of seven minutes.
- After five minutes of operating the appliance, shut off fuel to the appliance to turn off the burner and continue to collect data for an additional two minutes (seven minute test total).
- If the appliance draws combustion air from inside test room, the CO₂ content and temperature in the combustion venting system at the vent termination shall be monitored during the test to establish the excess-air level in the combustion vent.
- The CO₂ content of the space adjacent to the test room should be measured immediately before and immediately after the seven-minute test to ensure contamination has not occurred. Install the combustion appliance in a well-sealed room

The results show that at 50 Pa depressurization, three of the appliances had essentially undetectable levels of combustion spillage. Three other appliances had low, but measurable combustion spillage (between 0.7 and 1.5%). One appliance had significant combustion spillage (13%). The appliance with significant spillage at 50 Pa depressurization displayed 3.5% spillage at 20 Pa depressurization. All other appliances had no measurable spillage at 20 Pa depressurization. At 5 Pa depressurization, all the appliances had no measurable spillage.

Ambient air contains about 425 ppm of CO₂, but can change from day to day. Calculations for combustion spillage take into account change of background CO₂. Combustion gases exhausted far away from the test area so they did not interfere with measurements. When vented directly into the room, CO₂ levels achieved about 1400 ppm. Only about 85% of the CO₂ was accounted for when they vented directly into the room and used their method (perhaps due to incomplete combustion).

Additionally, oscillations in measurements were on the order of 15 ppm. Therefore, differentiating between a close “pass” and close “fail” could be difficult. Repeatability of tests was about 4%. It must be stressed that only one sample of each appliance was actually tested in this project. Sample to sample production changes and differences in the installation methods or materials may produce different results.

The authors conclude that the test is a simple method of differentiating products that spill and do not spill. Mostly, this tool is developed for combustion appliance manufacturers to test their appliances under different depressurization conditions. Additionally, the 2% spillage limit threshold was chosen to allow for flexibility in choice of instrumentation. This is the same tolerance allowed in the static vent leakage tests for the combustion vent section of sealed combustion appliances that operate with positive vent pressures.

A4.19 Depressurization Spillage Testing of Ten Residential Gas-Fired Combustion Appliances (2008)

This report [16] builds on similar research carried out in 2005, report titled, “Development and Evaluation of a New Depressurization Spillage Test for Residential Gas-Fired Combustion Appliances” [15], which evaluated the performance of a small sample of residential combustion appliances using a new depressurization spillage test procedure. Ten more new direct vent or power vent “spillage-resistant” gas appliances were tested at the same laboratory as the 2005 tests. The results of the new experiments were similar to those for the 2005 tests. At 50 Pa depressurization, five appliances had no measureable spillage. Three had low, but measureable spillage and two had more than 2% spillage, including one with over 10% spillage. Overall, combustion appliances that are designed to be spillage resistant do not perform as well as advertised, though they are much more resilient than natural draft appliances when interior depressurization occurs. This report further supports manufacturers using the new spillage test to identify appliances with problems and improve appliance performance. With this simple test, manufacturers can develop and market more spillage resistant combustion appliances. The appliances with the largest spillage for this research and the 2005 research were direct vent fireplace inserts.

A5 EFFECTS OF WIND ON HOUSE DEPRESSURIZATION AND VENT TERMINATION

Wind can affect house depressurization and combustion appliance venting. Some research has been conducted to determine the effects of wind on residential building depressurization; however, significantly less literature is available for effects of wind on vent caps. Commonly, wind flowing horizontally or upward over a chimney creates low pressure that produces increased draft. Wind blowing downward into the chimney or blowing against a nearby structure taller than the chimney can adversely affect draft. Additionally, the type of vent cap can have a significant effect on whether or not the combustion appliance vents properly while wind is present. Although many codes and standards (see Section A2 of this literature review) provide guidelines for vent and chimney termination design that help eliminate negative effects of wind on the vent exit, the only requirement stated about the vent cap is that each vent must have an appropriate vent cap. In the following sections, research investigating the effects of wind on internal pressure and the effects of wind on vent caps is summarized.

A5.1 Effects of Wind on Internal Pressures

Holmes [29] measured the mean and fluctuating pressures inside buildings induced by high winds using a boundary layer wind tunnel and computer simulation techniques. He found that the mean fluctuating internal pressure coefficients increase monotonically with increasing windward/leeward open area ratio, which agreed with theory. For a single windward opening, wind tunnel measurements and computer simulated data showed resonance effects on the fluctuating internal pressures. The resonant frequency increases and the damping decreases with increasing open area. Additionally, resonant frequencies do not contribute greatly to the total root-mean-square (RMS) pressure fluctuations. The author implied that the effects of higher wind velocities can be simulated by distorting the internal volume by a factor equal to the square of the velocity ratio.

Stathopoulos et al. [50] experimentally investigated wind-induced internal pressures using models of low-rise buildings of different geometry and internal volume. Three basic models were constructed, each containing variable side-wall and end-wall openings as well as three background porosities (0%, 0.5%, and 3.0% of the total surface area). The results show that internal pressures fluctuate significantly, but the overall magnitudes are less than that of local external pressures. The gust factor (the ratio of the peak pressure to the mean) is approximately two in open country. Additionally, fluctuations in internal pressure show little or no spatial variation except in regions close to dominant openings. For windward openings, internal pressure coefficients are positive except for cases with high background porosity combined with small openings, in which case they become zero or negative. The largest internal pressures occur when the wind direction is perpendicular to the wall with the dominant opening. When the downwind side of the structure contains the dominant opening and the windward wall is closed, then the internal pressures are generally negative and insensitive to the size of the wall opening or the background porosity.

Modera and Wilson [38] examined the potential for reducing the effect of wind on fan pressurization measurements of air leakage. Their research does not investigate the effects of wind on overall house depressurization, but is still relevant to this literature review. Experiments were conducted using multiple fan-pressurization tests on a single test house under variable wind conditions. The results show that by incorporating time averaged pressure signals, time averaged flow signals, and four-wall surface-pressure averaging, unbiased leakage area measurements with a scatter less than 11% can be obtained from fan pressurization measurements at wind-speeds up to 5 m/s. The CGSB pressure-averaging probe generally caused a negative bias in the measured leakage area at high wind speeds. Modera and Wilson also show that choosing the appropriate reference for the indoor-outdoor pressure differential is critical for fan pressurization measurements. They recommend implementing noise-reduction filtering and averaging techniques to fan pressurization tests.

A5.2 Effects of Wind on Vent Caps

The purpose of a vent cap is to prevent rain and debris from penetrating the venting system and to resist adverse effects caused by the wind. Many vent-cap designs claim to prevent

downrafting and wind driven rain entry. However, very little literature is available verifying the effectiveness of these vent caps.

UL 441 [52] provides requirements and tests for vent and vent cap design. It includes a test for determining the draft loss and wind effects on installed vent caps. The “Draft Loss and Wind Effects Test” is subdivided into three tests.

- The first test evaluates the vent cap impedance on flue flow for no wind. Static pressure inside the vent is measured with and without the vent cap. The difference in static pressure measurements cannot exceed 0.034 in.w.c (about 8.5 Pa).
- The second test evaluates the vent cap impedance on flue flow when subject to 20 mph wind conditions at a series of elevation angles ranging from 45 degrees below the horizontal to 45 degrees above the horizontal, in 15 degree intervals. Again, static pressure is measured inside the vent when uncapped and capped. The average difference in static pressure cannot not exceed 0.068 in.w.c. (about 17 Pa) at a horizontal wind front and at the three angles below horizontal or at a horizontal wind front and at the three angles above the horizontal.
- The third test evaluates the vent cap effect on the intended upward draft when subject to 20 mph wind conditions at a series of elevation angles ranging from 45 degrees below the horizontal to 45 degrees above the horizontal, in 15-degree intervals. For this test, the inlet to the gas vent is sealed so no air is flowing through the vent. Static pressure inside the vent is measured while wind is applied to the cap at different angles. The average pressure inside the vent must be equal to or less than 0.034 in.w.c. (about 8.5 Pa) below atmospheric pressure. Additionally, no pressure measurements can exceed atmospheric pressure.

Haysom and Swinton [27] were one of the first to report on the influence of flue caps (vent caps) on vent performance. They studied the effects of wind on four vent cap designs using a wind tunnel. The tests were conducted on common configurations of furnace and fireplace vent terminations to determine the horizontal and vertical wind pressure coefficients. Vent performance simulation results (likely from FLUESIM) were compared with experimental results. Three key features of a cap were identified: 1) its ability to moderate updraft in horizontal winds, 2) its ability to dampen the effects of updrafting or downrafting winds, and 3) the amount of restriction to flow it creates. Three performance parameters were suggested based on key features of the cap: 1) the cap’s horizontal wind pressure coefficient, 2) the cap’s vertical wind pressure coefficient, and 3) the effective flow area (EFA) of the cap or chimney exit. Their results showed that with a 20 km/h (12 mph) wind speed, for almost all wind angles tested, the vent caps could develop more than enough driving pressure to counteract the most severe house depressurization. The authors recommended that vent caps be tested at various wind speeds and approach angles rather than at a single set condition, as outlined in UL 441. They also recommended that a rating system for vent caps be developed for choosing appropriate vent caps for given house conditions.

Han et al. [26] investigated “venturi-type” vent caps for exhaust fans. The purpose of their study was to improve vent cap design to minimize energy consumption by exhaust fans and

improve performance. They compared their results to a vent without a vent cap. Wind speed was varied from 0 to 30 m/s, wind direction was varied from 0 to 90 degrees (0 degrees being parallel to the wall/roof surface), and exhaust pressure was varied from 0 to 100 Pa.

The ASHRAE Handbook – HVAC Systems and Equipment [1] provides some information regarding effects of wind on vent caps. The Handbook states that chimneys are required to be a minimum of 3 feet above the roof so small sparks will burn out before falling on the roof shingles. For satisfactory dispersion with low, wide buildings, chimney height must still be determined as if the height of the building is equal to the width of the building.

The Handbook also states that wind over a chimney can either impede or assist draft. If a chimney is located on the windward side of a wall or a steep roof, the wind can create a positive static pressure that impedes flow and results in backdrafting. Chimneys located near the surface of a less steep or flat roof can aid draft because the roof surface is under negative static pressure, but the wind velocity over the chimney is low. Taller chimneys experience greater wind velocity, which increases the draft. Because both chimney height and roof incline can affect chimney drafting, providing protocols for optimizing draft is difficult.

Pitched roofs can create either a positive or negative pressure over the chimney. According to the Handbook, the windward side of a roof with a pitch angle from 0 to 30° can create complete or partially negative pressures on the chimney or vent termination. The windward side of a 45° pitched roof creates strongly positive pressures on the chimney or vent termination. Steeper pitch roofs approach pressures observed on a vertical wall facing the wind. Wind velocities and pressures vary not only with pitch, but also with position between the ridge and eaves and in the horizontal direction of the pitched roof. Results for the leeward side are not presented. Tall chimneys exposed to full wind velocity can create strong venting updrafts. The updraft effect relative to wind dynamic pressure is related to the Reynolds number. If a vent cap is not present, then the open top can be sensitive to wind angle and rain. Proprietary vent caps have been designed to stabilize wind effects and improve performance.

Many compromises have been made in vent termination design, sacrificing some of the updraft created by the wind. According to the Handbook, the following performance features are important for vent cap design: still-air resistance, updraft ability with no flow, and discharge resistance when vent gases are carried at low velocity in a typical wind (3 m/s vent velocity in a 9 m/s wind). The Handbook also states, “test standards outlined by UL 441 take into account these aspects of performance to ensure adequate vent capacity.” Additionally, vent caps with high still-air resistance should be avoided.

A6 PATENTS RELATING TO SPILLAGE AND BACKDRAFTING

Viner et al. [53] patented a design for a backdrafting alarm assembly for combustion heating devices. The alarm measures temperature at several locations around the draft hood of the combustion appliance. If temperatures exceed 130°F over a sustained period (about 3 minutes), an alarm sounds.

Zimmermann et al. [56] patented a design for a flue gas sensor that continuously measures CO, NO_x, and O₂ located under the appliance draft hood near the exhaust outlet, but not directly in the exhaust stream. The inventors show a combustion appliance monitor design that is not affected by temperature so it can be directly inserted into the exhaust flow in the vent. If the monitor measures high amounts of CO, indicating spillage, then the monitor shuts off the appliance. Their sensor is mainly designed to measure hot exhaust gases from the vent and reduce the temperature of the exhaust gases before reaching the gas analyzer.

A7 SIMULATION SOFTWARE FOR COMBUSTION APPLIANCE VENTING SYSTEMS AND HOUSE VENTILATION

This section focuses on software that simulates venting, spillage, backdrafting, and/or depressurization. The section includes a brief description of various software packages and reviews literature on model validation.

Two software packages are available for simulating gas appliance venting. The first, VENT-II, is capable of predicting transient operation of venting systems serving one or two appliances. The second, FLUESIM, is capable of predicting the effect of the whole house system (including the envelope, chimney or vent, combustion appliance, exhaust appliances, weather, flue cap design) on venting performance of the combustion appliance.

Building envelope depressurization from wind and the use of mechanical systems can be modeled using CONTAM. CONTAM is capable of predicting building airflows, contaminant concentrations, and personal exposure. Further details for each software package are provided in the following sections.

A7.1 Gas Appliance Simulation Software

A7.1.1 VENT-II

VENT-II is a computer program designed to provide detailed analysis of gas appliance venting systems, including the transient effects of appliance cycling. The program calculates temperatures, pressures, flows, priming times (time it takes to heat up the vent system), and flue gas condensation throughout the vent system. The program is capable of modeling one or two fan-assisted or natural draft gas appliances on a single vent [18]. The program reportedly has been validated for common types of venting systems using venting guidelines for Category I gas appliances [47]. These venting systems include single-wall metal vents, Type B vents, plastic pipe vents, tile-lined masonry chimneys, and masonry chimneys that have been relined for use with gas appliances.

The first version of VENT-II was released for public purchase in 1991 and was labeled Version 4.1. Version 5.0 was released to operate using the Microsoft Windows 95/NT environment. The current version, 5.3, uses the same equations and code as Version 4.1, but is capable of operating

using the Windows XP/Vista/7 environment. Additionally, Version 5.3 allows the user to print reports about the vent system being modeled and to export graphs and tables of simulation output for use in other programs. The appearance of graphs is also customizable.

VENT-II uses classical fluid flow, heat transfer, and mass transfer theory to predict venting performance, which includes calculating external natural convection, internal forced and natural convection, mass transfer of water vapor between the vent gas and the vent wall, condensation heat transfer, heat transfer through the vent wall, available draft, mass flow, and pressure loss.

The program calculates available draft using the difference between outdoor-air density and mean gas density in each section. The ideal gas law is assumed for calculating the vent gas density, which means the density is inversely proportional to vent gas absolute temperature. The draft in each vent region is calculated using:

$$Draft = \sum_{i=1}^{N_s} P_{nat,i} \quad (A2)$$

where, $P_{nat} = (\rho_0 - \bar{\rho}_f)gH$, ρ_0 is the density of air outside the vent at the elevation of the vent section (kg/m^3), $\bar{\rho}_f$ is the mean density of the vent gas in the vent section i (kg/m^3), g is the gravitational constant (m/s^2), H is the height of the vent section (m), and N_s is the total number of vent sections in the vent connector or common vent. Vent system performance parameters as a function of time are calculated by dividing the vent system into sections. A transient (time-varying) calculation is necessary for determining condensation in the vent system. The time step in VENT-II is fixed at 5 seconds.

For vent systems with two appliances, VENT-II can only predict vent flow for the scenarios listed in Table A46. VENT-II handles a single appliance as Appliance 1 and assumes Appliance 2 is fan-assisted with a very large loss coefficient in order to suppress the vent connector flow. Leakage at section joints is also calculated. Initial conditions assumed in VENT-II are summarized in Table A47.

Table A46: VENT-II Configuration Scenarios

Appliance Scenario Number	Appliance 1		Appliance 2	
	Type*	Operating State	Type*	Operating State
1	ND	Any	ND	Any
2	ND	Any	FA	Off
3	ND	Any	FA	On
4	FA	Off	FA	Off
5	FA	On	FA	Off
6	FA	On	FA	On

*ND = Natural Draft, FA = Fan-Assisted

Although VENT-II has been used for predicting vent system performance, cited validation reports were not easily obtained. A related article written by Rutz and Leslie [48] concludes that designing and constructing vent systems that follow protocols in the National Fuel Gas Code can resolve the majority of venting problems associated with fan-assisted gas appliances. However, VENT-II can be used to go beyond the scope of National Fuel Gas Code. One should note that the sizing tables provided in Chapter 13 of the National Fuel Gas Code [39] were generated using the VENT-II computer program.

Table A47: VENT-II Initial Conditions

Parameter	Initial Condition
Wall Temperature	Ambient Temperature
Heat Loss/Gain	None
Condensate	None
Flue Gas Temperature	Ambient Temperature
Flue Gas Flow	Zero
Flue Gas composition	Air
Vent System Draft	None
Vent System Flow, percent of on-cycle combustion flow rate	Draft-hood system: 30% Fan-assisted system: 10%

A more recent article written by Glanville et al. [21] provides research validating VENT-II by comparing VENT-II results with results from a computational fluid dynamics (CFD) software package (Fluent, Version 6.3). This study primarily focused on relining requirements related to upgraded venting systems with masonry chimneys. Performance of these chimneys was assessed using VENT-II, Fluent, and measured data. The authors stated that VENT-II is a one-dimensional nodal model, solving a reduced form of the Navier-Stokes equations and a semi-empirical condensation model at the interior flue surface. Fluent was setup using the k- ϵ turbulence model. Compared to Fluent, the authors state that VENT-II provided “sufficiently accurate” predictions for condensation. VENT-II, Fluent, and experimental results confirm the relining recommendations in the National Fuel Gas Code venting tables for the cases studied. In their results, they present data for condensation rates, but do not provide experimental or numerical data showing temperatures or pressures in the chimney. The authors state that temperature and pressure were measured during their experiments, but did not compare the measurements with VENT-II results.

A7.1.2 FLUESIM

FLUESIM is a computer program developed for the Research Division of Canada Mortgage and Housing Corporation (CMHC) in the 1980's. It simulates a whole house "system", including the building envelope, chimneys, furnaces, and exhaust appliances. It can simulate a wide variety of indoor and outdoor conditions and was developed as a research tool for studying the performance of various furnace/flue systems and their interaction with the building and other mechanical systems. The program was originally used to gain a better theoretical

understanding about indoor air quality problems related to combustion appliance backdrafting and spillage. FLUESIM can also be used to prevent circumstances that may lead to venting problems [49].

The program takes into account several different effects on venting performance including, but not limited to, size and mass of the vent connector and chimney, indoor and outdoor temperature difference, the flue location (interior or exterior), airtightness of the building, location of make-up air openings, cross-envelope flows, wind action at the top of the flue and on the envelope, presence of flue dampers and caps, and type of furnace (oil or gas). Experimental test data on flue caps is also provided for different wind angles and chimney material types. Although FLUESIM is a very powerful tool, it requires 180 user inputs to fully describe the system and conditions being simulated, making it impractical to use onsite [49].

A research house owned by CMHC was used to provide initial field data for validating the software. These data were then used to calibrate and fine tune FLUESIM. The user's manual [49] does not contain data or experiments validating FLUESIM, but does include a list of background research papers that contain more information regarding the inner working of the model and its algorithms. The manual recommends a study conducted in 1987 [20] in which experimental data from 21 houses, identified to have spillage problems, were used to further validate FLUESIM. The program confirmed that many factors contributed to combustion venting problems and that venting problems with a chimney depend not only on its own characteristics and location, but also on the circumstances in which it is required to operate. The modeling and survey results also showed that spillage from conventional fireplaces is virtually certain in all but the leakiest houses and that conventional glass doors provide no additional protection against spillage.

A7.2 Building Contamination, Depressurization, and Infiltration Simulation Software

A7.2.1 CONTAM

CONTAM is a multizone indoor air quality and airflow network analysis computer program designed to determine:

- Building system airflows: infiltration, exfiltration, and room-to-room flows driven by mechanical means, wind pressures acting on the exterior of the building, and buoyancy effects induced by indoor, outdoor, and interzone air temperature differences.
- Contaminant concentrations: the dispersal of contaminants transported by airflows; transformed by a variety of processes including chemical and radio-chemical transformation, adsorption and desorption to building materials, filtration, and deposition to building surfaces; and generated by a variety of source mechanisms.
- Personal exposure: exposure of occupants to airborne contaminants for risk assessment.

CONTAM88 was a combination of the National Bureau of Standards (now the National Institute for Standards and Technology, NIST) pollutant transport (CONTAM87) and airflow network (AIRNET) simulation tools. CONTAM94 added a GUI to facilitate input entry. CONTAMW appeared in about 2000.

Since its original release, CONTAM has included several new features including contaminant-related libraries, separate weather and ambient contaminant files, building controls, scheduled zone temperatures, and an improved solver to reduce simulation time. CONTAM can simultaneously calculate multizone airflows and pressures to assess the adequacy of ventilation rates in a building, determine the variation in ventilation rates over time, and assess the impact of envelope air tightening on zone depressurization. The program requires inputs such as building component characteristics (e.g., zone nodal heights, flow path resistances and locations, duct leakage), weather, contaminant generation rates, and occupant locations and schedules. With these inputs, CONTAM can predict contaminant concentrations, which can be used to determine the indoor air quality performance of a building. Predicted contaminant concentrations can also be used to estimate personal exposure based on building occupancy patterns. Because CONTAM does not have an embedded thermal model, it is not capable of predicting venting performance, backdrafting events, or spillage events without being linked to a thermal model (e.g., VENT-II, FLUESIM, TRNSYS).

A8 LITERATURE GAPS AND CONCLUSIONS

Established methods for evaluating the safety of residential combustion appliance venting systems produce results that are not directly relatable to risk. Current standard tests do not state a clear risk management objective, nor are they conducted in a manner that provides a clear indication of the risk of spillage during normal operation. A key deficiency is that they do not explicitly account for the fact that backdrafting and spillage are both physical and statistical phenomena. The zero risk tolerance implied in current standards may be harming energy efficiency efforts – by limiting air sealing – without appreciably increasing occupant safety. It is also possible that current test methods do not always identify problematic conditions.

Backdrafting and spillage occur when there is a confluence of contributing physical elements. Those elements include appliance and venting systems that are vulnerable to spillage based on sizing, materials, and configuration; characteristics of mechanical systems that contribute to house depressurization; appliance and other mechanical system use patterns; weather; and building component air tightness. Air sealing to improve envelope air tightness and the installation or upgrade of exhaust fans can both increase depressurization of interior spaces and thus increase the likelihood of backdrafting and spillage of natural draft combustion appliances. Combustion safety tests are employed to assess whether air tightening will or has created an untenable spillage hazard. Mitigation options include limiting air sealing – which sacrifices energy-savings potential directly – or installation of power-venting combustion appliances and/or some engineered capacity for make-up air; the latter measures may divert funds that could be applied to other measures that achieve greater energy efficiency benefits.

Induced stress tests that create nominal “worst case” conditions could be understood as seeking zero risk tolerance. Stress tests and long term monitoring approaches that allow (do not treat as failures) occurrences of transient spillage that occur just after the main burner ignites can still be regarded as having implicit no-risk targets; transient spillage events of a few minutes or less do not release enough pollutant mass to substantially impact indoor air quality. Specifying a clear risk mitigation objective is important when trying to assess if an appliance and venting configuration is problematic, and especially if a test is effective at finding problematic installations.

For a no-risk standard, there are two essential questions that are relevant to assessing the robustness of any specific test. (1) Does the test “fail” or identify as problematic, appliance and venting installations that do not produce sustained backdrafting and spillage in use? (2) Does the test “pass” or not identify as problematic some appliance and venting installations that actually produce sustained backdrafting and spillage during use? The former can be characterized as misleading test failures; the latter can be characterized as misleading passes. The concept of a misleading test result is also relevant to probability-based metrics.

As described in Section A4, most of the research assessing the performance of established methods involves comparing the results of different test methods applied to the same appliances. Monitoring under natural use conditions is logically understood to assess actual backdrafting and spillage. Consistent with this framework, the results of stress-induced tests typically have been evaluated in reference to monitoring results. Results from the studies that have employed this approach are inconclusive with respect to the two questions noted above. Most of the in-use monitoring has focused on houses failing stress-induced tests. Across the studies, varying but generally small fractions of houses that fail the stress tests are found to have backdrafting and spillage in practice. However, the one-week duration of monitoring that occurred in most of the published studies may be too short to reliably conclude that the studied appliances and houses will not have any incidences of spillage over the course of a typical year. Extensive monitoring has not been conducted in houses that pass stress-induced tests. The reliability of such tests to identify all houses that are at risk is therefore unresolved.

A more productive research focus has been to identify characteristics of appliances, venting systems, and houses that fail the stress-induced tests. Key findings are that failures are often associated with improperly sized or installed venting systems, and/or improperly installed combustion equipment. Bohac and Cheple [7] found that venting systems that were properly sized and met code standards [39] were more likely to vent properly and pass stress-induced tests. Additionally, equipment that is serviced, tuned, and maintained is more likely to vent properly and produce less harmful pollutants, such as CO and NO_x. Fugler [19] presented research suggesting that spillage events are more strongly correlated with appliance and venting system configuration than with effects of outside temperature and wind. Fugler additionally suggested that poor chimney performance is likely the largest contributing factor to combustion spillage. However, Fugler did not provide data showing the effects of wind and temperature on stress-induced tests.

Existing research examining the link between combustion spillage with occupant health is limited. Research primarily focuses on CO and neglects other hazards associated with spillage, such as NO_x and moisture related problems. According to a study conducted by Wilson et al. in 1993 [54], 95% of homes (277 total) tested continuously over 48 hours met the maximum 1-hour and 8-hour CO limits. The maximum 1-hour and 8-hour California standards for CO are 20 ppm and 9 ppm, respectively. A report investigating non-fire CO deaths associated with consumer products from 2007 [28] states that 2% of the 184 CO related deaths (from 2005 to 2007) were caused by water heaters, 2% were caused by ranges and ovens, 14% were caused by furnaces, and 17% were caused by other heating systems (i.e., portable, unvented heaters). These results suggest that acute CO poisoning from vented combustion appliances is extremely rare. However, more research is required to investigate both acute and chronic CO poisoning associated with vented combustion appliances.

The effects of weather variation, especially for wind, on stress-induced test methods have not been adequately assessed in published research. Despite the large research efforts to date, the tests and standards currently in use are insufficient for predicting if natural and unsealed induced-draft combustion appliances are venting safely. Research conducted by Koontz et al. [34] is the only available research focusing on how weather conditions affect stress test results. Their results showed that houses were more likely to fail stress tests during low wind speeds than high wind speeds; however, more research needs to be conducted to further understand the relationship between wind speed and venting performance. The authors did not find a definitive correlation between outdoor temperature and stress tests, but did suggest that water heaters are more likely to fail when outside temperatures exceeded 60°F. Bohac and Cheple [7], however, showed spillage failure increased significantly when the outside temperature exceeds 40°F. Because little research is available assessing the relationship between outdoor temperature and stress test failure, more research is required.

Haysom and Swinton [27] showed that vent caps performed well at wind speeds of about 12 mph and were able to establish draft even when the house was depressurized. However, no research is available assessing vent cap performance under low or zero wind conditions. UL 441 requires vent caps to meet specified requirements for wind speeds of 0 and 20 mph at different angles, but might be accepting vent caps that could be problematic under low wind conditions or in some locations where local static pressures are increased due to wind stagnation or deflection by adjacent surfaces. In some cases, because vent caps are not tested for their performance over a range of wind conditions, appliance drafting could be competing with downdrafting caused by presence of low wind conditions, but draft properly if no wind or high wind was present. Further investigation is required for testing the performance of vent caps under a range of wind conditions, especially low wind conditions.

In principle, the likelihood of backdraft and spillage can be assessed for a wide range of equipment and venting configurations and weather using either of the two existing simulation software programs: VENT-II or FLUESIM. However, we found no published reports of either program being applied for this purpose. Even basic documentation about the performance of these programs in comparison to experiments is lacking in the archival literature. VENT-II provides outputs for sizing vent systems, but does not take into account effects of wind or

depressurization of the combustion appliance zone. Additionally, validation reports for VENT-II are difficult to obtain. FLUESIM provides outputs for predicting spillage, but reports showing how it was validated are difficult to obtain. CONTAM is a useful tool for determining CAZ depressurization, but CONTAM cannot independently predict combustion appliance performance, backdrafting, or spillage. Further research exploring the use of these computer programs for predicting venting performance, backdrafting, and spillage is required.

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APPENDIX B:

Predicting Backdrafting and Spillage for Natural-Draft Gas Combustion Appliances: Validating VENT-II

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B1 INTRODUCTION

VENT-II is a computer program that was developed for analyzing the performance of a vent system serving one or two natural-draft gas appliances or the single vent serving a fan-assisted appliance (Detty et al. 1998, Rutz et al. 1992). It has been used to generate the current vent sizing tables in the National Fuel Gas Code (NFPA 2012), which is referred to by U.S. building codes and standards. VENT-II is also cited in the ASHRAE Handbook – HVAC Systems and Equipment as a tool for analyzing chimney performance and steady-state chimney design (ASHRAE 2012).

The program calculates temperatures, pressures, flows, and flue gas condensation for each section of the vent system. These calculations are based on classical fluid flow, heat transfer, and mass transfer theory, and include phenomena such as external natural convection, internal forced and natural convection, mass transfer of water vapor between the vent gas and the vent wall, condensation heat transfer, heat transfer through the vent wall, available draft, mass flow, and pressure loss. Vent system performance parameters are calculated as a function of time. The transient (time-varying) calculation is especially necessary to represent startup dynamics and for determining condensation inside the vent system. The time step in VENT-II is fixed at 5 seconds (Rutz et al. 1992).

The available draft, or pressure drop, in the vent system is calculated by summing the pressure difference across each section in the vent system:

$$\text{Draft} = \sum_{i=1}^{N_s} \Delta P_i \quad (\text{B1})$$

where i is the vent section, N_s is the total number of vent sections, and ΔP_i is the total pressure difference across each vent section. The total pressure difference across each vent section is calculated using:

$$\Delta P_i = (\rho_0 - \bar{\rho}_i)gH_i \quad (\text{B2})$$

where ρ_0 is the outdoor-air density (kg/m^3), $\bar{\rho}_i$ is the mean gas density in vent section i (kg/m^3), g is the gravitational constant (9.81 m/s^2 or 32.2 ft/s^2), and H_i is the vent height of section i (m).

The ideal gas law is used for calculating the vent gas density, such that the mean density in each vent section is inversely proportional to the mean vent gas temperature.

VENT-II's temperature, pressure, flow, and condensation predictions reportedly have been validated for a variety of vent systems (Glanville et al. 2011, Rutz et al. 1992, Rutz and Leslie 1993). These validation reports, however, are not readily available and do not clearly address the program's ability to predict combustion appliance zone (CAZ) depressurizations that lead to combustion gas spillage into the CAZ. This ability is important because it can define a key vent system characteristic that, when combined with separate knowledge about CAZ depressurization and indoor combustion gas concentration statistics (magnitude and frequency), can determine whether a vent system can operate safely (Rapp et al. 2012). The purpose of this report is to validate whether VENT-II can be used to predict combustion appliance zone depressurizations that lead to spillage.

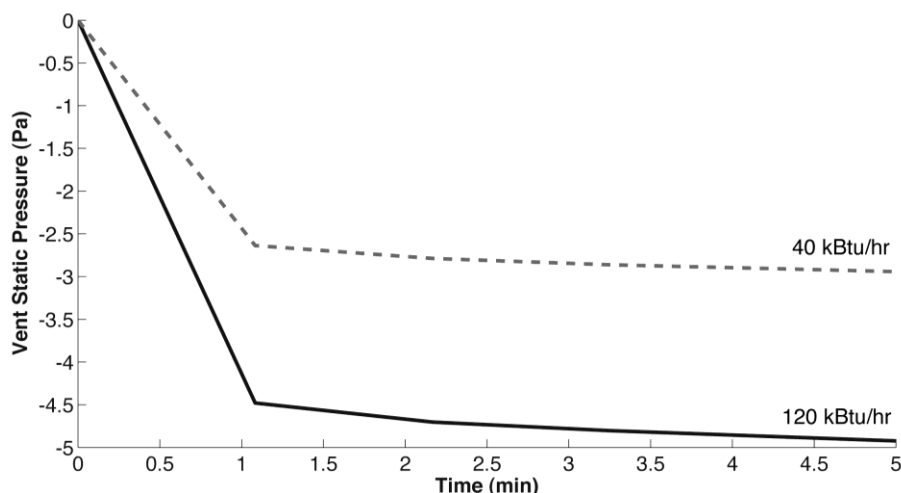
Following this introduction, we provide a detailed description for differentiating between backdrafting and spillage using VENT-II. Next, we describe the simulation and experimental setup for each vent system that we considered: four appliance and vent system configurations, each with a different set of outdoor temperature conditions (cold, mild, or hot). Then, we present and analyze the results. In the final section, we provide conclusions and recommendations.

B2 IDENTIFYING SPILLAGE EVENTS IN VENT-II

Experimental research has shown that simply measuring or predicting static pressure at the vent entry relative to the CAZ pressure can be misleading when attempting to identify spillage events (Grimsrud and Hadlich 1999; Koontz et al. 1999, Koontz et al. 2001, Nagda et al. 2002). For example, an appliance with an undersized vent system can have a negative static pressure in the vent relative to the CAZ, indicating the appliance is drafting, and yet still spill exhaust gases into the living space. Spillage occurs because the vent capacity limits the amount of dilution air and exhaust gases flowing through the vent system.

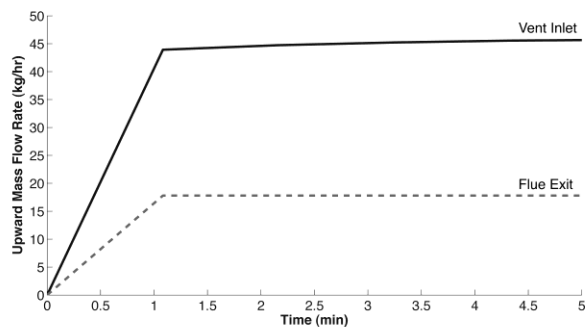
To illustrate this case, we used VENT-II to simulate venting for two appliances: a 40 kBtu/hr (11.7 kW) appliance with an appropriately sized vent system and a 120 kBtu/hr (35.2 kW) appliance with a vent system sized for a 40 kBtu/hr (11.7 kW) appliance (NFPA 2012). As expected, the pressure in the vent for both appliance simulations was negative, as shown in Figure B1, indicating that the appliance is drafting.

Figure B1: Vent static pressure remains negative in the vent system when the appliance is appropriately sized (40 kBtu/hr or 11.7 kW) and when the appliance is oversized (120 kBtu/hr or 35.2 kW), even though the oversized appliance spills combustion gases into the living space, as shown in Figure B2.

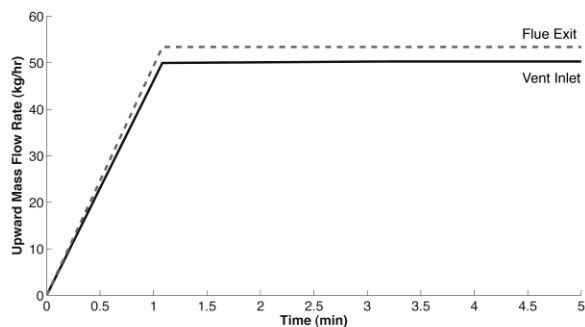


For the 40 kBtu/hr (11.7 kW) appliance, Figure B2(A) shows that mass is gained from the flue outlet to the vent inlet, which indicates that dilution air is entering the vent and spillage is not occurring. However, Figure B2(B) shows that mass is lost between the flue outlet and vent inlet for the 120 kBtu/hr (35.2 kW) appliance, which indicates that the appliance is spilling. In this report, we assumed that simulated vent systems with a loss in mass between the flue and vent are spilling and we used simulated vent static pressure to indicate if the appliance was drafting (negative vent static pressure) or backdrafting (positive vent static pressure).

Figure B2: For a 40 kBtu/hr appliance with an appropriately sized vent system (A), the mass flow rate of gases at the flue outlet is less than the mass flow rate of gases in the vent, which indicates that dilution air is entering the vent and the appliance is not spilling. However, for an oversized 120 kBtu/hr (35.2 kW) appliance using the same vent system sized for a 40 kBtu/hr (11.7 kW) appliance (B), the mass flow rate of gases at the flue outlet is greater than the mass flow rate of gases in the vent, which indicates that the appliance is spilling.



(A) 40 kBtu/hr Appliance



(B) 120 kBtu/hr Appliance

B3 SIMULATION AND EXPERIMENTAL SETUP

We assessed VENT-II's ability to predict combustion gas spillage events due to house depressurization by comparing VENT-II simulated results with experimental data (vent static pressure during baseline conditions and CAZ depressurization resulting in spillage) for four appliance-vent systems. These systems included:

- a common-vented water heater and furnace system located in Twin Cities, Minnesota;
- a single-vented orphaned water heater located in Berkeley, California;
- a single-vented orphaned water heater located in Stockton, California; and
- a single-vented wall furnace located in Stockton, California.

As described in Section B3.1, experimental data for the system in Twin Cities, Minnesota were taken from a report written by Grimsrud and Hadlich (1995). For the other three systems, we collected the performance data. The remainder of this section provides a detailed description of each vent system and describes the other data that we used or collected to model each system.

B3.1 Central Furnace and Water Heater in Twin Cities, Minnesota

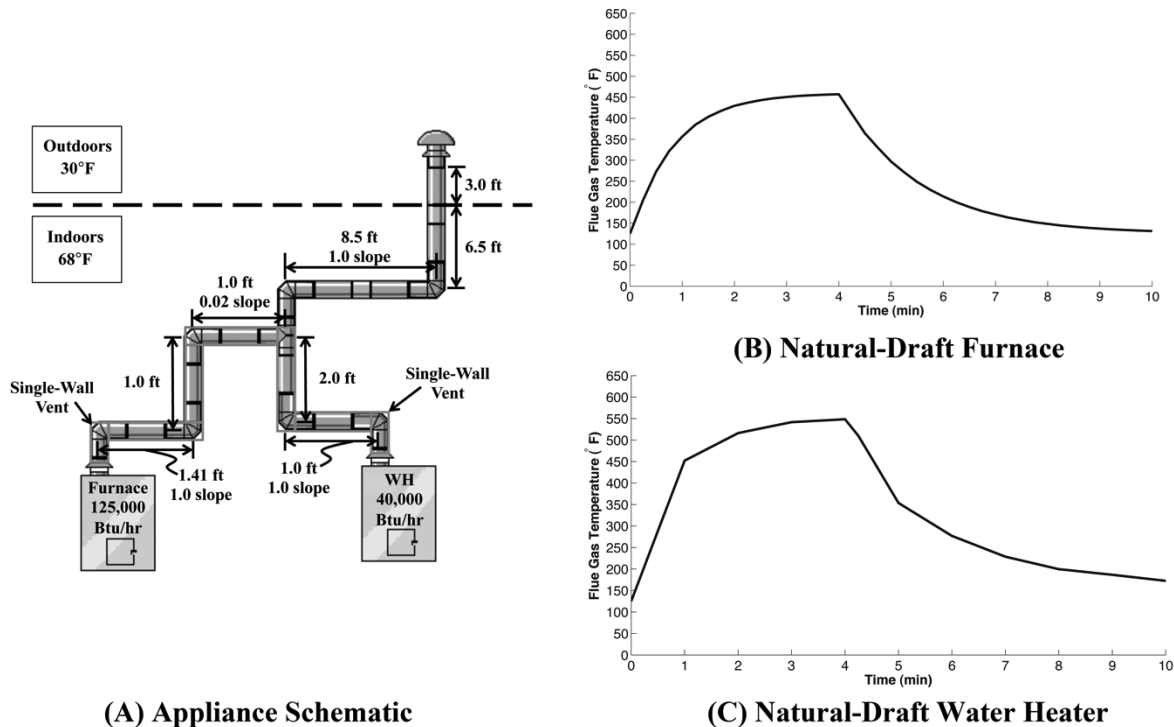
Grimsrud and Hadlich (1995) developed and field tested a protocol that evaluates the impact of house depressurization on backdrafting and spillage of naturally-vented combustion appliances. They found that three of the ten homes that they tested were spillage prone. One of these three homes had a common-vented natural-draft furnace and water heater vent system (located in Twin Cities, Minnesota and titled EP2 in their report) and enough information was provided in their report so that we could simulate the vent system using VENT-II.

According to the report: "The water heater vent connector is a 4 inch (10.16 cm) diameter duct with two 90° elbows before the drip-T. The furnace vent connector is 6 inch (15.24 cm) diameter with three 45° elbows before the drip-T. After the drip-T, the vent has two 45° elbows. A section of the vent runs diagonally through the garage before exiting vertically through the garage roof" The lengths of each individual vent section were not provided, but dimensions of the basement, first floor, and second floor were given. Using these floor dimensions, we approximated the length of each vent section. It should be noted that changing lengths of the runs by 1 foot (30.48 cm) had no effect on simulated drafting and spillage results. Figure B3 shows a schematic of the common-vented appliances that we modeled in VENT-II. Table B1 provides the appliance ratings and operating conditions for the furnace and the water heater.

Table B1: Appliance ratings and operating conditions for common-vented natural-draft furnace & water heater system located in Twin Cities, MN (EP2) (Grimsrud & Hadlich 1995).

Indoor Temperature °C (°F)	Outdoor Temperature °C (°F)	Outdoor Relative Humidity %	Excess Combustion Air for Both Appliances %	Barometric Pressure kPa (in. Hg)	Furnace Input Rating kW (kBtu/hr)	Water Heater Input Rating kW (kBtu/hr)
20 (68)	-1 (30)	22	30	101 (29.9)	36.6 (125)	11.7 (40)

Figure B3: Schematic of furnace and water heater vent system in Twin Cities, MN as modeled in VENT-II (A) and the simulated flue gas temperature for the furnace (B) and the water heater (C) during one operating cycle. The furnace vent connector is composed of two, 6 in. (15.24 cm) diameter single-walled vents. The water heater (WH) vent is composed of two circular, 4 in. (10.16 cm) diameter single-walled vents. The common vent contains four circular, 6 in. (15.24 cm) diameter B-vents. Horizontal sections with slopes greater than or equal to 1.0 are assumed to have 45-degree elbows. Horizontal sections with slopes less than 1.0 are assumed to have 90-degree elbows.



Grimsrud and Hadlich performed 4 minute long spillage tests at three combustion appliance zone (CAZ) pressures with respect to outdoors: a baseline pressure (no exhaust appliances operating) of -2.5 Pa (-0.010 in.w.c.), -7.5 Pa (-0.030 in.w.c.), and -9.0 Pa (-0.036 in.w.c.). The CAZ was initially depressurized by operating the range hood and then further depressurized by operating both the range hood and the dryer. For each spillage test, they reported the CAZ depressurization and whether the appliance was backdrafting and spilling or drafting and not spilling. Differential vent pressure, which was measured at the base of the common vent, was recorded only for the baseline pressure condition, -2.5 Pa (-0.010 in.w.c.).

Grimsrud and Hadlich did not provide appliance flue temperature profiles for the natural draft furnace and water heater, but they did state that each appliance was operated for 4 minutes. To model this common vented system in VENT-II, we used the program's default natural draft furnace flue temperature profile to approximate the furnace and reduced the firing time to 4 minutes. We used the flue temperature profile from the orphaned water heater in Stockton, California to approximate the water heater in Grimsrud and Hadlich's report. This profile was chosen because the age of the water heater closely matched the age of the water heater in their report. We adjusted the firing time of the temperature profile from 12 minutes to 4 minutes in

the model to match the firing time listed in their report. The modeled flue gas temperature profiles for the furnace and the water heater are also shown in Figure B3.

B3.2 Water Heater in Berkeley, California

This 1907 two-story Berkeley, California home contains an orphaned water heater located in the laundry room on the first floor. A schematic of the water heater, as modeled in VENT-II, is shown Figure B4. We expected that this system would be susceptible to spillage at low house depressurizations because the vent system contains two runs with 90-degree elbows and one of the runs does not meet the National Fuel Gas Code minimum slope requirement (1/4 inch or 6.35 mm, per horizontal foot). Table B2 provides the appliance rating and operating conditions.

Figure B4: Schematic of the vent system modeled in VENT-II (A) and the measured flue gas temperatures (B) of the orphaned water heater located in Berkeley, CA. The vent connector is composed of two circular, 3-in. (7.62 cm) diameter single-walled vents. The common vent contains four circular, 3-in. (7.62 cm) diameter B-vents. All elbows are 90-degrees.

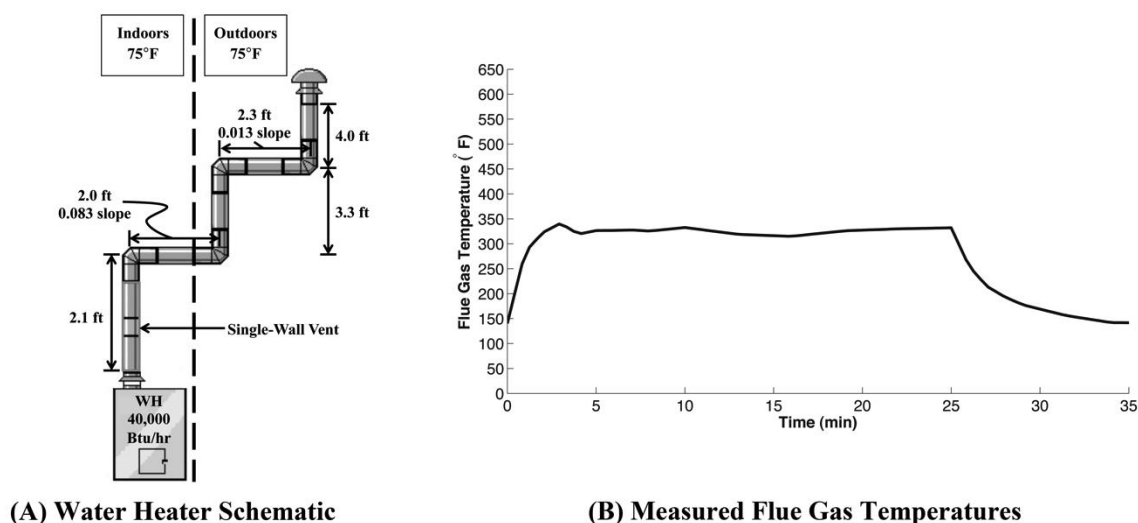


Table B2: Appliance rating and operating conditions for the natural draft water heater system located in Berkeley, CA.

Indoor Temperature	Outdoor Temperature	Outdoor Relative Humidity	Excess Combustion Air	Barometric Pressure	Water Heater Input Rating
°C (°F)	°C (°F)	%	%	kPa (in.Hg)	kW (kBtu/hr)
24 (75)	24 (75)	55	33	100 (29.5)	11.7 (40)

Following the protocols outlined in the National Fuel Gas Code (NFPA 2012) and the Whole House Combustion Safety Test Procedure (PG&E 2011), we conducted a “draft test” at three CAZ pressures relative to outdoors: baseline of 0.0 Pa, -2.0 Pa (-0.008 in.w.c.), and -3.0 Pa (-0.012 in.w.c.). For the “draft test”, we used a smoke pen to identify whether spillage was occurring 5 minutes after appliance start-up. Exterior doors and windows remained closed for the duration of the test while interior doors remained open. A blower door was used to depressurize the CAZ until upward flow in the vent could not be established within 5 minutes. The vent system was allowed to cool to ambient conditions between depressurized “draft tests”.

To fully characterize the vent system in VENT-II, we also measured the following: barometric pressure, CAZ depressurization with respect to outdoors, vent temperature and static pressure with respect to the CAZ (measured 1 ft., 30.48 cm, above the draft diverter as recommended by BPI (2012), CAZ temperature, outdoor temperature, flue temperature, excess combustion air, percent excess air in the flue, and carbon monoxide (CO) concentration in the flue. Vent static pressure was monitored only at the baseline CAZ pressure because when the CAZ was depressurized, vent static pressures fluctuated greatly and a meaningful measurement could not be obtained. Prior to depressurizing the house, we measured the flue gas temperature each minute for a complete operating cycle as shown in Figure B4, ensuring that the appliance reached a steady state flue gas temperature before the burner was turned off. If spillage occurred, we measured its duration using a smoke pen for up to 5 minutes before the appliance was shut-off.

An Energy Conservatory Automatic Performance Testing (APT) System connected to a computer was used to measure differential pressures and indoor and outdoor air temperatures. A Testo 327-1 Combustion Analyzer Kit was used to measure flue temperature, vent temperature, excess air in the flue, and carbon monoxide in the flue. Barometric pressure was measured using a Gulf Coast Data Concepts B1100-1 USB Data Logger. Outdoor relative humidity and wind speed were obtained from a local weather station.

B3.3 Water Heater and Wall Furnace at the PG&E Test House in Stockton, California

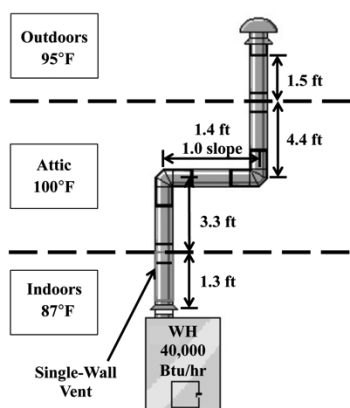
The Pacific Gas and Electric Company (PG&E) test house is a single-story building with an attic located at their Energy Training Center in Stockton, CA. The purpose of the training center is to provide continuing education for businesses, construction professionals, and participants of energy efficiency education programs. We chose this house for testing because it contains several appliances, among which are an orphaned water heater and a wall furnace, and it could be used during hot weather conditions.

B3.3.1 Water Heater

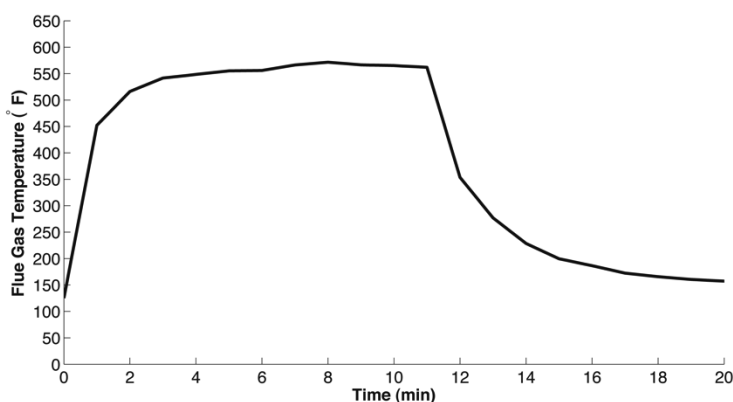
The water heater is located in the laundry room adjacent to the kitchen. A door can be closed to separate the laundry room from the kitchen, but this door remained open during the duration of our test so that the CAZ could be depressurized directly using a blower door. A schematic of the VENT-II model for the water heater is shown in Figure B5. Table B3 provides the appliance rating and operating conditions. The same test procedures and measurements conducted in the

Berkeley, California home were also conducted on the orphaned water heater in Stockton, California. Figure B5 also shows the measured flue temperature profile for the water heater during one operating cycle. The “draft test” (assessing whether spillage was occurring five minutes after appliance start-up) was conducted at four CAZ pressures relative to outdoors: baseline of 0.0 Pa, -5.5 Pa (-0.022 in.w.c.), -9.0 Pa (-0.036 in.w.c.), and -11.0 Pa (-0.044 in.w.c.).

Figure B5: Schematic of the vent system modeled in VENT-II (A) and the measured flue gas temperatures (B) of the orphaned water heater at the PG&E Test House in Stockton, CA. The vent connector is composed of one circular, 3-in. (7.62 cm) diameter single-walled vent and three circular, 3-in. (7.62 cm) diameter B-vents. The common vent contains one circular, 3-in. (7.62 cm) diameter B-vent. The elbows are 45-degrees.



(A) Water Heater Schematic



(B) Measured Flue Gas Temperatures

Table B3: Appliance rating and operating conditions for the natural-draft water heater system located in Stockton, CA.

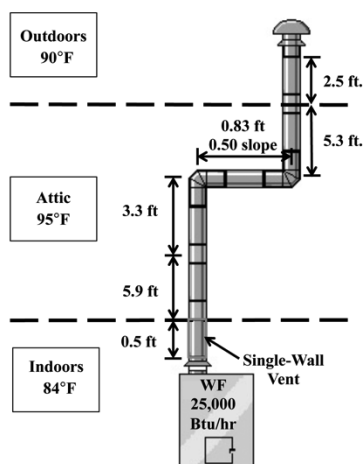
T_{CAZ}	T_{out}	T_{attic}	Outdoor Relative Humidity	Excess Combustion Air	Barometric Pressure	Water Heater Input Rating
°C (°F)	°C (°F)	°C (°F)	%	%	kPa (in.Hg)	kW (kBtu/hr)
31 (87)	35 (95)	38 (100)	13	30	100 (29.6)	11.7 (40)

B3.3.2 Wall Furnace

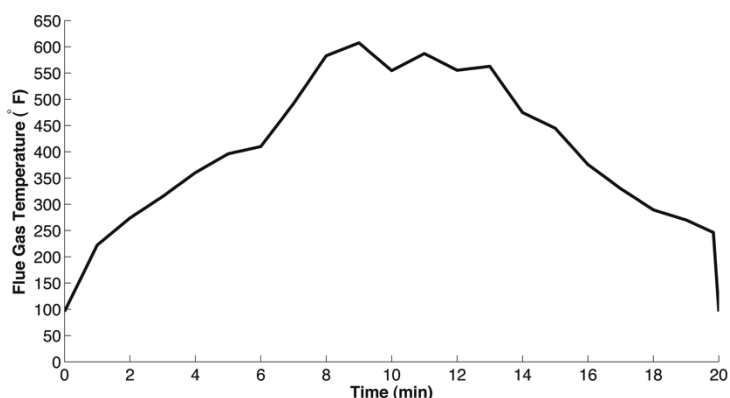
We also conducted a “draft test” on the wall furnace located in the living room, even though operation of the wall furnace during summer conditions is unlikely. The purpose of this test was to determine VENT-II’s ability to predict drafting and spillage in a vent system that changes shape. For this furnace, the vent is square just after the draft diverter, then connects to

an oval vent and finally to a circular vent. A schematic of the wall furnace modeled in VENT-II is shown in Figure B6. Table B4 provides the appliance rating and operating conditions. The same procedures conducted for the orphaned water heater in Berkeley, California were used for the wall furnace. Figure B6 also shows the measured wall furnace flue temperature profile for one operating cycle. The “draft test” was conducted at three CAZ pressures relative to outdoors: baseline of 1.5 Pa (0.006 in.w.c.), -9.0 Pa (-0.036 in.w.c.), and -12.0 Pa (-0.048 in.w.c.).

Figure B6: Schematic the vent system modeled in VENT-II (A) and the measured flue gas temperatures (B) of the wall furnace at the PG&E Test House in Stockton, CA. The vent connector is composed of a single-wall rectangular vent, 1-in. (2.54 cm) x 4.5-in. (11.43 cm), an oval B-vent, 2-in. (5.08 cm) x 7-in. (17.78 cm), and two circular, 4-in. (10.16 cm) diameter B-vents. The common vent contains four circular, 4-in. (10.16 cm) diameter B-vents. The elbows are 90-degrees.



(A) Wall Furnace Schematic



(B) Measured Flue Gas Temperatures

Table B4: Appliance rating and operating conditions for the natural-draft wall furnace system located in Stockton, CA.

T_{CAZ}	T_{out}	T_{attic}	Relative Humidity	Excess Combustion Air	Barometric Pressure	Water Heater Input Rating
°C (°F)	°C (°F)	°C (°F)	%	%	kPa (in.Hg)	kW (kBtu/hr)
30 (86)	32 (90)	35 (95)	26	30	101 (29.9)	7.3 (25)

B4 RESULTS AND DISCUSSION

To determine whether VENT-II can be used to predict CAZ depressurizations leading to five minutes of continuous combustion appliance spillage (spillage depressurization), we compared simulated results with experimental data for four appliance configurations and three outdoor temperature conditions. We found that VENT-II accurately predicts spillage for appliances operating in cold and mild conditions, but had difficulty predicting spillage for appliances in hot conditions. Following the comparison of simulated and experimental results, we describe simulation problems that we encountered.

B4.1 Depressurization-Induced Spillage

For each VENT-II simulation, an appliance was considered to spill when mass was being lost to indoors at the draft diverter (i.e., when the predicted mass flow of exhaust gas in the vent was less than the mass flow of exhaust gas leaving the flue). Similar to the experimental results, spillage events lasting five or more minutes in the simulation were considered to fail the National Fuel Gas Code “draft test” (NFPA 2012). As described in Section B2, vent static pressure with respect to the CAZ was not used as an indicator of spillage because an appliance can have a negative vent static pressure and still spill (i.e., for undersized vents). Instead, vent static pressure was only used to determine whether the appliance was backdrafting (downward flow) or drafting (upward flow). For the baseline CAZ pressure case (no exhaust appliances operating), we compared the simulated vent static pressure with experimental results.

B4.1.1 Spillage Depressurization for Common Vented System in Twin Cities, Minnesota

Grimsrud and Hadlich (1995) tested the common-vented furnace and water heater located in Twin Cities, MN for spillage, independently, during winter conditions. Their experimental results showed that the flow in the furnace vent was upward at the baseline CAZ pressure of -2.5 Pa (-0.010 in.w.c.) relative to outdoors and there was no spillage. When the CAZ pressure was -7.5 Pa (-0.030 in.w.c.), the furnace spilled for 90 seconds before establishing upward flow. At a CAZ pressure of -9.0 Pa (-0.036 in.w.c.), the furnace spilled for the duration of the test (4 minutes). The water heater, which was tested when the CAZ pressure was -7.5 Pa (-0.030 in.w.c.), spilled during the 4 minutes of testing.

In general, the VENT-II results agree well with the experimental results, as shown in Table B5. Figure B7 shows that VENT-II predicted that the furnace will backdraft and spill for about 10 seconds before establishing upward draft when the CAZ pressure is -7.5 Pa. When the CAZ pressure is -9.0 Pa, VENT-II predicted that the furnace will spill for the duration of the test (4 minutes). Figure B8 shows that VENT-II predicted that the water heater will backdraft and spill for the duration of the test when the CAZ pressure is -7.5 Pa. Although VENT-II could predict whether depressurization-induced spillage would occur for the furnace and water heater at each pressure condition, the predicted vent static pressure for the furnace under baseline conditions (-2.7 Pa, -0.011 in.w.c.) was almost twice the measured value (-1.5 Pa, -0.006 in.w.c.). Additionally, the predicted spillage time for the furnace at the -7.5 Pa CAZ pressure was 80 seconds shorter than that measured.

Much like the experimental data, VENT-II predicted that the spillage depressurization for the furnace was between -7.5 Pa and -9.0. However, the exact spillage depressurization could not be determined using VENT-II because it continuously gave a computational error at depressurizations between -7.5 Pa and -8.5 Pa (-0.030 and -0.034 in.w.c.). At -8.5 Pa, VENT-II predicted the appliance would spill for 4 minutes. The solver error associated with VENT-II is discussed further in Section B4.2.2.

Table B5: Measured and simulated spillage states and vent static pressures for natural-draft appliances located in Twin Cities, MN during winter conditions.

Appliance	CAZ Pressure Pa (in.w.c.)	State* (Spill / No Spill)		Vent Static Pressure Pa (in.w.c.)	
		Measured	VENT-II	Measured	VENT-II**
Furnace	-2.5 (-0.010)	No Spill	No Spill	-1.5 (-0.006)	-2.7 (-0.011)
Furnace	-7.5 (-0.030)	90 sec. Spill	10 sec. Spill	N/A	-1.7 (-0.007)
Water Heater	-7.5 (-0.030)	Spill	Spill	N/A	2.2 (0.009)
Furnace	-9.0 (-0.036)	Spill	Spill	N/A	2.7 (0.011)

* "Spill" indicates that the appliance spilled exhaust gases into the CAZ for the duration of the test (4 minutes). A time (i.e., 90 seconds) indicates that the appliance initially spilled for that duration and then did not spill for the remainder of the test. "No Spill" indicates that the appliance did not spill at any time.

** Vent static pressure 4 minutes after appliance start-up.

Figure B7: VENT-II predicted that the common-vented furnace located in Twin Cities, MN will spill (A) and backdraft (B) for the duration of the test (4 minutes) when the CAZ pressure, with respect to outdoors, is -9.0 Pa (-0.036 in.w.c.). When the CAZ pressure is -7.5 Pa (-0.030 in.w.c.), VENT-II predicted that the appliance will backdraft for about 10 seconds before establishing upward draft but would not spill. No spillage or backdrafting was predicted at a CAZ pressure of -2.5 Pa (-0.010 in.w.c.).

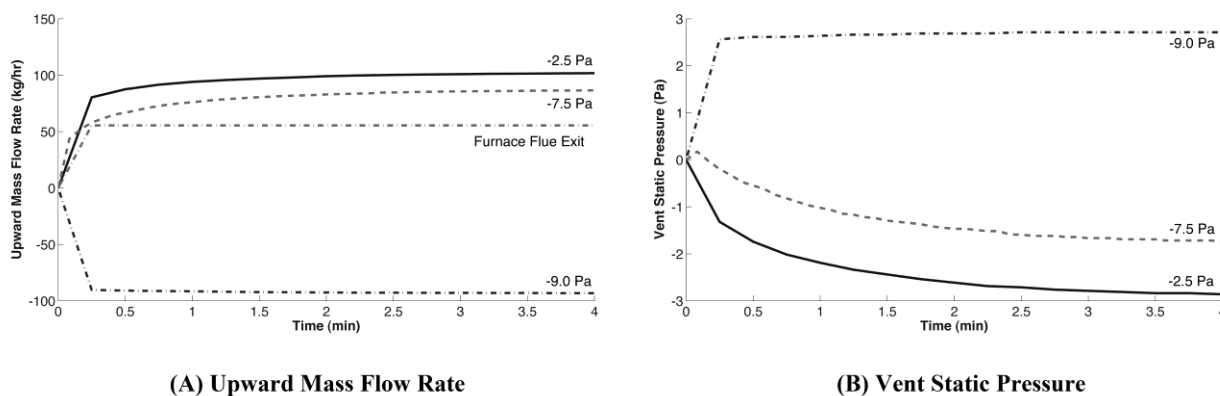
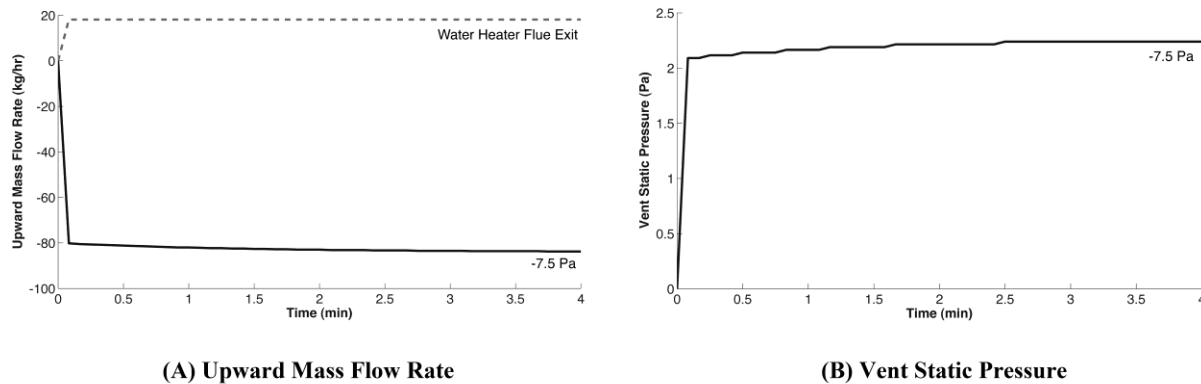


Figure B8: VENT-II predicted that the common-vented water heater located in Twin Cities, MN will spill (A) and backdraft (B) for the duration of the test (4 minutes) when the CAZ pressure, with respect to outdoors, is -7.5 Pa (-0.030 in.w.c.).



B4.1.2 Spillage Depressurization for the Orphaned Water Heater in Berkeley, California

We tested the orphaned water heater located in Berkeley, CA for spillage during summer conditions. It should be noted that summer conditions in Berkeley are similar to spring or fall conditions in most other parts of the United States, given that the outdoor temperature (75°F) was the same as the indoor temperature. Our experiments showed that, for baseline conditions (0.0 Pa), the water heater drafted upward and there was no spillage. When the CAZ pressure was -2.0 Pa (-0.008 in.w.c.), the water heater fluctuated between spilling and no spilling for the duration of the test. When the CAZ pressure was -3.0 Pa (-0.012 in.w.c.), the water heater spilled continuously.

The simulated results from VENT-II show good agreement with the experimental results for this appliance (Table B6). For the baseline CAZ pressure, VENT-II results match experimental data: it predicted a vent static pressure of -1.8 Pa (-0.007 in.w.c.), and that the appliance will draft upward and not spill. However, when the CAZ pressure was -2.0 Pa, Figure B9 shows that VENT-II predicted that the appliance will spill for almost 2 minutes. For the appliance to spill for the duration of the test (5 minutes), VENT-II predicted that the CAZ pressure should be -2.5 Pa (-0.010 in.w.c.), while experimental results indicate -3.0 Pa (-0.012 in.w.c.). Figure B9 also shows that backdrafting coincided with the spillage events.

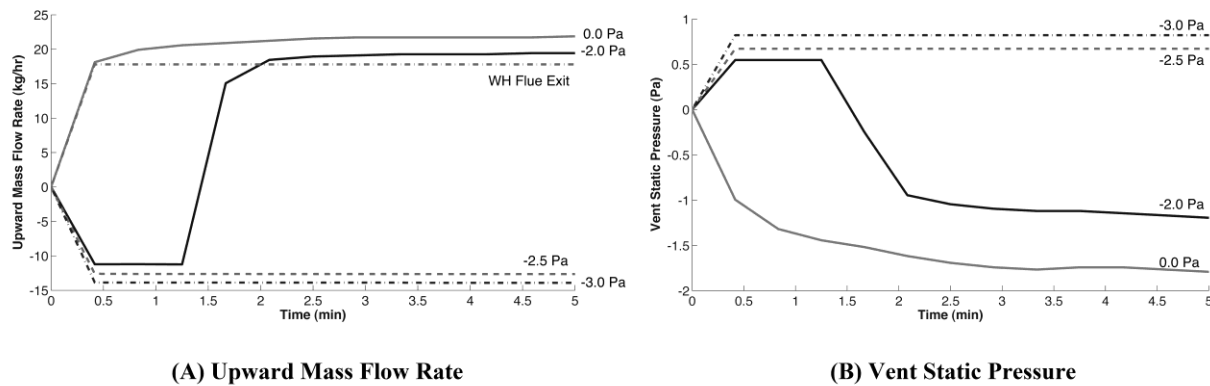
Table B6: Measured and simulated spillage states and vent static pressures for the orphaned water heater in Berkeley, CA during summer conditions.

CAZ Pressure Pa (in.w.c.)	State* (Spill / No Spill)		Vent Static Pressure Pa (in.w.c.)	
	Measured	VENT-II	Measured	VENT-II**
0.0 (0.0)	No Spill	No Spill	-1.8 (-0.007)	-1.8 (-0.007)
-2.0 (-0.008)	Fluctuating Spill	2 min. Spill	N/A	-1.2 (-0.005)
-3.0 (-0.012)	Spill	Spill	N/A	0.7 (0.003)

* “Spill” indicates that the appliance spilled exhaust gases into the CAZ for the duration of the test (5 minutes). A time (i.e., 2 minutes) indicates that the appliance initially spilled for that duration and then did not spill for the remainder of the test. “Fluctuating Spill” indicates that the appliance fluctuated between spilling and not spilling for the duration of the test. “No Spill” indicates the appliance did not spill at any time.

** Vent static pressure 5 minutes after appliance start-up.

Figure B9: VENT-II predicted that the orphaned water heater located in Berkeley, CA will spill (A) and backdraft (B) for the duration of the test (5 minutes) when the CAZ pressure, with respect to outdoors, is less than or equal to -2.5 Pa (-0.010 in.w.c.). The water heater was also predicted to spill and backdraft for almost 2 minutes before establishing upward flow when the CAZ pressure was -2.0 Pa (-0.008 in.w.c.).



B4.1.3 Spillage Depressurization for the Orphaned Water Heater in Stockton, California

We tested the orphaned water heater located in Stockton, CA for spillage during summer conditions. The water heater drafted upward and did not spill at the baseline CAZ pressure (0.0 Pa) or when the CAZ pressure was -5.5 Pa (0.022 in.w.c.) relative to outdoors. When the

CAZ pressure reached -9.0 Pa (-0.036 in.w.c.), the water heater fluctuated between spilling and not spilling for the 5 minute duration of the test. When the CAZ pressure was -11.0 Pa (-0.044 in.w.c.), the water heater spilled continuously for the duration of the test.

As shown in Table B7, VENT-II correctly predicted spillage depressurization, but did not correctly predict vent static pressure. VENT-II also predicted about 40 seconds of spillage when the CAZ pressure was -5.5 Pa when no spillage occurred during the experiment.

Table B7: Measured and simulated spillage states and vent static pressures for the orphaned water heater in Stockton, CA during summer conditions.

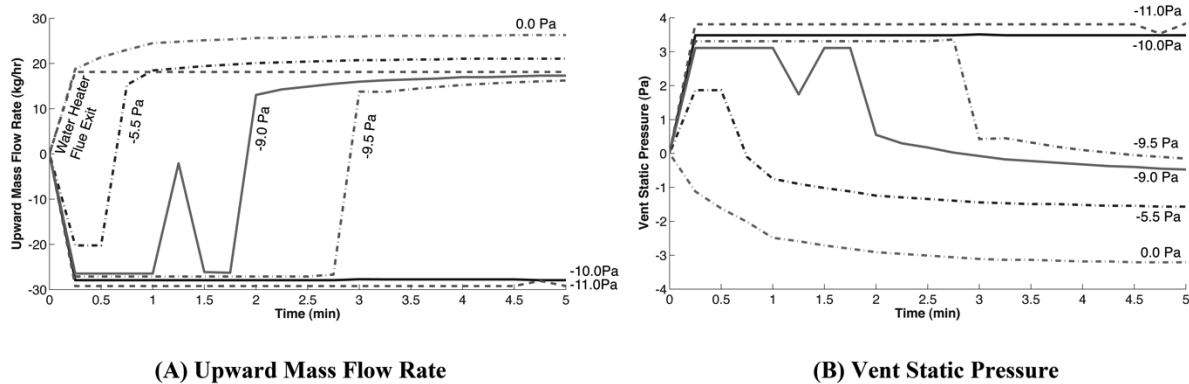
CAZ Pressure Pa (in.w.c.)	State* (Spill / No Spill)		Vent Static Pressure Pa (in.w.c.)	
	Measured	VENT-II	Measured	VENT-II**
0.0 (0.0)	No Spill	No Spill	-8.2 (-0.033)	-3.2 (-0.013)
-5.5 (-0.022)	No Spill	40 sec. Spill	N/A	-1.5 (-0.006)
-9.0 (-0.036)	Fluctuating Spill	Spill	N/A	-0.5 (-0.002)
-11.0 (-0.044)	Spill	Spill	N/A	3.7 (0.015)

* “Spill” indicates that the appliance spilled exhaust gases into the CAZ for the duration of the test (5 minutes). “Fluctuating Spill” indicates that the appliance fluctuated between spilling and not spilling for the duration of the test. “No Spill” indicates that the appliance did not spill at any time.

** Vent static pressure 5 minutes after appliance start-up.

When the CAZ pressure was -9.0 Pa, VENT-II predicted that the appliance will spill for the duration of the test, as shown in Figure B10, even though an upward draft was established after about 3 minutes. These results could be predicting some of the fluctuation between spilling and not spilling that occurred during our measurements. The 20 kg/hr (44 lbm/hr) increase and then decrease in simulated upward mass flow rate between 1 minute and 1.5 minutes for a CAZ pressure of -9.0 Pa will be addressed in Section B4.2. When the CAZ pressure was -9.5 Pa (-0.038 in.w.c.), VENT-II predicted that the water heater will spill for the duration of the test, but will backdraft for about 4.5 minutes (see Figure B10). Figure B10 also shows that VENT-II predicted a spillage depressurization of -10.0 Pa (-0.040 in.w.c.) if the appliance is to spill and backdraft continuously for 5 minutes, while the experimental results showed continuous spillage at -11.0 Pa for the duration of the test.

Figure B10: VENT-II predicted that the orphaned water heater located in Stockton, CA will spill (A) and backdraft (B) for the duration of the test (5 minutes) when the CAZ pressure, with respect to outdoors, is less than or equal to -10.0 Pa (-0.040 in.w.c.).



B4.1.4 Spillage Depressurization for the Wall Furnace in Stockton, California

The wall furnace in Stockton, California also was tested for spillage during summer conditions. At the baseline CAZ pressure, 1.5 Pa (0.006 in.w.c.), the furnace drafted upward and did not spill. At -9.0 Pa (-0.036 in.w.c.), the furnace spilled for the duration of the test (5 minutes). As shown in Table B8, at the baseline CAZ pressure, VENT-II predicted no spillage, like the experimental results, and under predicted the vent static pressure as it did for the water heater. VENT-II could not predict vent static pressure or mass flow rate through the vent system for a CAZ depressurization greater than -3.7 Pa (-0.015 in.w.c.) because the solver continually failed. At a CAZ pressure of -3.7 Pa (-0.015 in.w.c.), as shown in Figure B11, VENT-II predicted that the furnace would spill and backdraft for about 1 minute before establishing an upward draft and no spillage. Problems with the solver are discussed further in Section B4.2.

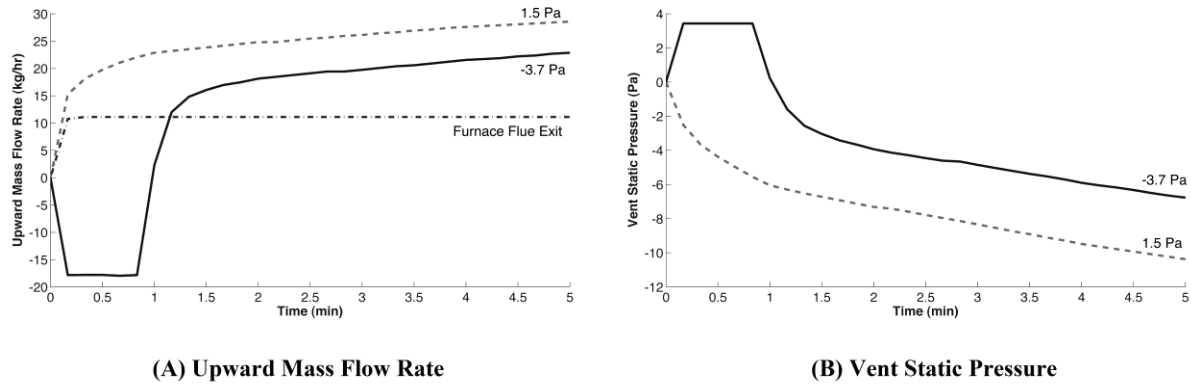
Table B8: Measured and simulated spillage states and vent static pressures for the wall furnace in Stockton, CA during summer conditions.

CAZ Pressure Pa (in.w.c.)	State* (Spill / No Spill)		Vent Static Pressure Pa (in.w.c.)	
	Measured	VENT-II	Measured	VENT-II**
1.5 (0.006)	No Spill	No Spill	-16.4 (-0.066)	-14.4 (-0.058)
-9.0 (-0.036)	Spill	N/A	N/A	N/A

* "Spill" indicates that the appliance spilled exhaust gases into the CAZ for the duration of the test (5 minutes). "No Spill" indicates that the appliance did not spill at any time.

** Vent static pressure 5 minutes after appliance start-up.

Figure B11: VENT-II was unable to predict the upward mass flow rate (A), or vent static pressure (B) for the wall furnace located in Stockton, CA when the CAZ pressure, with respect to outdoors, is greater than -3.7 Pa (-0.015 in.w.c.). Although not shown here, VENT-II predicted no spillage or backdrafting for the baseline CAZ pressure, 1.5 Pa (0.006 in.w.c.).



B4.2 Simulation Problems

We encountered two types of problems when using VENT-II to simulate vent systems. The first type was vent section location for single-appliance models. The second type was errors in the solver resulting in incomplete or erroneous solutions.

B4.2.1 Vent Section Location for Single-Appliance Models

When creating a model for the orphaned water heater in Stockton, CA, we found that the predicted spillage depressurization was highly sensitive to vent configuration (i.e., a vent can be a part of the vent connector or a part of the common vent). The VENT-II manual does not clearly state the difference between the vent connector and the common vent for single-appliance vent systems. Therefore, we simulated the water heater using four different configurations (see Figure B12) with the same boundary conditions to explore how predicted spillage depressurizations change. For the first configuration (Figure B12A), the water heater vent system was designed such that the vent protruding through the roof was part of the common vent while the remainder of the vent system was part of the vent connector. In this case, VENT-II predicted a spillage depressurization of -10.0 Pa (-0.040 in.w.c.). If the vent configuration is changed to match Figure B12B, then the predicted spillage depressurization is -6.5 Pa (-0.026 in.w.c.). As vent sections are moved from the vent connector to the common vent, the predicted spillage depressurization decreases, as shown in Table B9.

Figure B12: Changes in vent configuration for the model of the orphaned water heater in Stockton, CA.

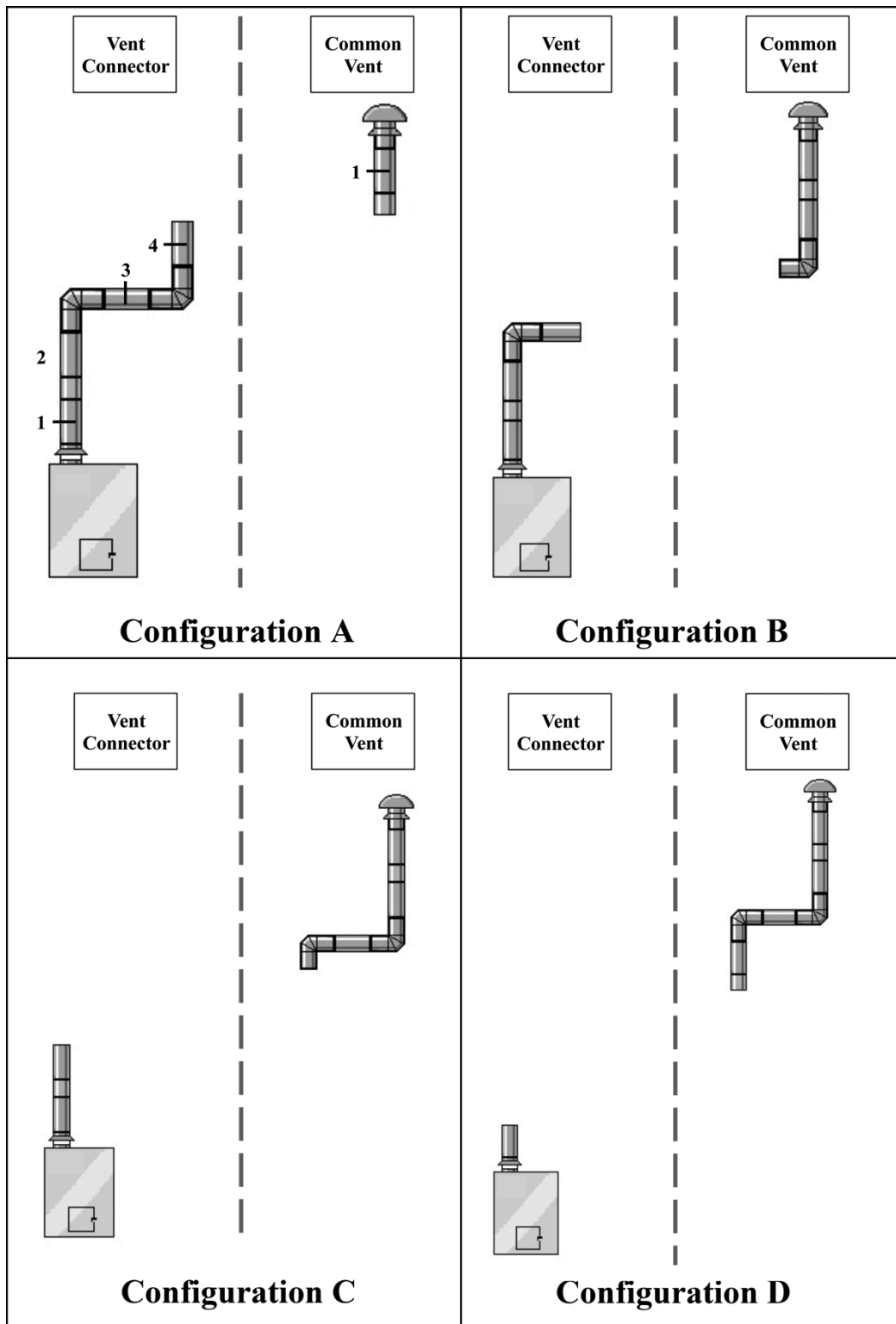


Table B9: VENT-II results when changing vent configuration of the water heater.

Configuration	Number of Vent Connector Sections	Number of Common Vent Sections	CAZ Pressure Causing Spillage Pa (in.w.c.)
A	4	1	-10.0 (-0.040)
B	3	2	-6.5 (-0.026)
C	2	3	-5.8 (-0.023)
D	1	4	-2.0 (-0.008)

The vent configuration for the orphaned water heater in Berkeley, CA was also changed, but the predicted spillage depressurization remained constant. These results suggest that pressure, temperature, and mass flow rate calculations for the common vent use the outdoor temperature, while calculations for the vent connector use the indoor temperature. Following this definition would suggest that external vents (vents located outside the house) should be modeled in the common vent while internal vents should be modeled in the vent connector. The authors of VENT-II should verify this assumption and provide more detailed instructions for modeling single-appliance vent systems in VENT-II. When modeling the single-appliance vent systems in Section B4.1, we assumed that internal vents are part of the vent connector and external vents are part of the common vent.

B4.2.2 Errors with the Solver

When running simulations in VENT-II, we frequently encountered inconsistencies with the solver. For several modeling conditions, VENT-II was either unable to converge to a solution or converged to an incorrect solution. When VENT-II was unable to converge to a solution, it would stop the solver and provide an error. For some models, the solver would complete part of the transient solution (stopping after two or three time steps) while in other models it would solve almost to the end of the defined appliance operating time before providing an error. When VENT-II converged to an incorrect solution, a sharp increase or decrease in the results for one time step was observed. For example, Figure B10 shows a sharp increase in mass flow rate at about 1.25 minutes when the CAZ pressure was set to -9.0 Pa (-0.036 in.w.c.). Other CAZ pressures, however, did not show this same phenomenon, thus indicating an error with the solver. One possible solution is to change the solver time step. VENT-II has a set time step of 5 seconds. In some cases, this time step may be too large to provide a convergent solution.

VENT-II also provided inconsistent errors when changing the depressurization for a model. For example, if the depressurization for the model of the orphaned water heater in Stockton, CA was set to -8.0 Pa (-0.032 in.w.c.), the solver did not provide solutions beyond the first minute of the operating cycle and displayed a solver error. However, when the depressurization was increased to -9.0 Pa (-0.036 in.w.c.), VENT-II was able to provide a solution for the entire operating cycle of the appliance without errors. These results suggest that solutions provided

beyond -8.0 Pa (-0.032 in.w.c.) might not be reliable even though the solver does not provide an error. From this study, we recommend that depressurizations leading to errors in the solver should be explored to increase the reliability of the solutions.

B5 CONCLUSIONS

The purpose of this report was to determine whether VENT-II could be used to predict combustion appliance zone (CAZ) depressurizations leading to combustion spillage (spillage depressurization) by comparing simulated results from VENT-II with experimental data from four vent systems. From this study, we came to the following conclusions:

- VENT-II correctly predicted spillage depressurization for appliances operating in cold and mild outdoor conditions, but could not accurately predict spillage depressurization for hot outdoor conditions. This indicates that VENT-II is not reliable for predicting spillage depressurization over the entire year, especially where hot conditions occur.
- For a single-appliance vent system, moving vent sections from the common vent to the connector vent in VENT-II changes the predicted spillage depressurization.
- The algorithm used in VENT-II's solver needs further investigation. In many cases, the solver converged to an incorrect solution at a given time step, but would correct itself for the next time step, leading to inconsistent results.
- VENT-II provided inconsistent errors when changing CAZ depressurization for a model. In some cases, a specific CAZ depressurization would cause the solver to fail, but increasing or decreasing the CAZ depressurization slightly (± 0.1 Pa, 0.0004 in.w.c.) would provide a complete solution.
- Due to inconsistent errors with the solver, an exact spillage depressurization could not be determined for a few cases. Therefore, VENT-II may not properly identify appliances that are spilling in practice.

Although VENT-II provides a first step towards modeling vent systems, further development is required to produce a reliable program that can correctly predict spillage caused by depressurization. From this study, we recommend that VENT-II's solver be investigated further and more detailed instructions be provided when modeling single-appliance vent systems.

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APPENDIX C:

Residential Combustion Gas Spillage: Impacts of Airtightness and Airflows on Indoor Air Pollutant Concentrations

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September 2014

C1 INTRODUCTION

Concerns about combustion appliance safety are interfering with residential building retrofit efforts to improve energy efficiency through air tightening. One particular concern is that tightening the building envelope increases the risk that mechanical exhaust ventilation will reverse the expected outward flow of combustion gases in appliance vents, thus pulling these gases into the conditioned space. Therefore, the building performance industry advocates exercising extreme caution when air tightening houses, to avoid backdrafting and spillage of combustion gases.

More specifically, during normal operation of a combustion appliance such as gas-fired water heaters and furnaces, the buoyancy of the hot combustion gases drives flow out of the house through the appliance vents. However, exhaust fans operating in ventilation devices such as range hoods, clothes dryers, and bathroom fans can sometimes reverse the flow through vents. This reversal of flow in the vent while the appliance is operating is known as *backdrafting*. A backdrafting appliance that spills combustion gases containing carbon monoxide (CO), nitrogen dioxide (NO₂), particles, and water vapor can increase indoor pollutant concentrations and associated health risks, including illness and, in extreme cases, death from CO poisoning.

Several field test methods are available for assessing the potential for fan-induced backdrafting and spillage [4, 6, 7, 27, 28, 30]. Most of these tests evaluate spillage potential for each combustion appliance by conducting a “worst-case” depressurization test, which attempts to maximize the fan-induced depressurization of the house. It does so by turning on all of the mechanical ventilation fans, and then configuring interior doors to maximize the negative pressure with respect to outdoors in the room where the combustion appliance is operating (known as the combustion appliance zone, or CAZ). The measured pressure *change* is then compared against a depressurization limit set by the testing protocol.

These tests postulate that the mechanically-induced “worst-case” depressurization has the greatest potential for reversing flow in the combustion appliance vent. However, previous research [5, 11, 17-19, 23, 29] has shown that the reliability of these tests is unresolved, and the related mitigation objectives are not clearly defined. In particular, these tests do not adequately assess the *risk* of spillage, for several reasons. First, the depressurization that the fans can achieve also depends in part on the weather at the time of the test and ignores the effects of

wind and temperature-difference induced outdoor air infiltration on depressurization in the absence of fan operation. Second, the conditions that lead to the “worst-case” depressurization, such as operating all exhaust fans simultaneously for an extended period of time, are potentially rare. For these two reasons alone, these tests do not assess the frequency with which an appliance may backdraft. Third, because the most hazardous conditions rarely correspond to the “worst-case” depressurization, a house potentially can pass the test yet have indoor air quality problems (or vice-versa). Finally, the field tests typically focus on indoor CO and appliance flue CO, but ignore other pollutants such as NO₂ (a respiratory irritant) and water vapor (which can result in mold). Thus, the tests do not assess the actual risk associated with combustion spillage.

The ultra-conservative “zero-risk, zero-harm, all the time” policy that is the basis for current combustion safety tests often comes with a high cost and undefined health benefit to the home occupants. The primary concern with combustion safety should be to prevent events that lead to illness or death. Therefore, instead of continuing to use costly combustion safety test methods that implicitly never allow indoor concentrations to exceed low level thresholds, affordable test methods that have a low probability of occasionally breaching low level thresholds are still needed.

For an individual house, long-term monitoring is the most certain method of determining the distribution of backdrafting and elevated pollutant concentration events (e.g., their frequency, duration, and severity). However, long-term monitoring can be expensive, and requires nontrivial expertise to collect and interpret the data. To overcome this barrier, in this report, we use simulations to investigate the pollutant concentrations that can occur indoors due to depressurization-induced backdrafting. Simulation studies are useful for identifying conditions that are likely to produce backdrafting, possibly motivating the use of long-term monitoring or other interventions. The simulations investigate the correlation between weather conditions, house depressurization, combustion spillage, and pollutant exposure. More specifically, we use the simulations to identify scenarios that could lead to high indoor pollutant concentrations resulting in illness or death. Through this research, our objectives are to provide a scientific basis for identifying the exposure risk associated with backdrafting appliances, for developing strategies to identify houses with potential problems, and ultimately for improving test methods.

Following this introduction, Section C2 provides background on the test procedures currently used to assess combustion safety, and the pollutant exposure limits used in our modeling studies. Next, Section C3 describes a basic pollutant transport model, which forms the basis for our three main simulation studies. This simplified box model yields insights into the role of variables such as the house volume, air change rate, and other factors that affect the generation and transport of combustion gases.

Sections C4, C5, and C6 describe three related simulation studies, which we designed to better understand the risk associated with house depressurization and combustion spillage. These sections are broken down into the following:

- The *spillage* study was designed to bound the problem under realistic conditions (Section C4). It shows the time evolution of indoor concentrations when a combustion appliance is spilling under a *constant* house depressurization, using realistic values for the house size, air tightness, emission rate, and emission duration. This study does not, however, specify the cause of the depressurization.
- The *airflow driver* study was designed to relate depressurization to airflows (Section C5). It examines, under steady-state conditions, how wind, indoor-outdoor temperature differences, and mechanical ventilation combine to establish the pressures and flows that determine backdrafting. This study identifies the key parameters that affect vent flow reversal, but does not examine the resulting indoor concentrations.
- The *yearly distribution* study was designed to combine the airflow and concentration models under realistic weather conditions (Section C6). It drives an indoor concentration model using observed yearly weather data from 16 California climate zones. This puts the previous results in context, by accounting for the actual distributions of the wind and temperature conditions that help set airflow.

Following the simulation studies, the final section summarizes modeling conclusions, discusses their implications, and provides recommendations for model improvements to support further work.

C2 BACKGROUND

Over the past 25 years, test methods for assessing the venting performance of combustion appliances have remained essentially unchanged. In 1988, the Canada Mortgage and Housing Corporation (CMHC) published one of the first guidelines for such a purpose, titled, “Procedures for Determining the Safety of Residential Chimneys” [31]. This test requires a visual inspection, a simplified house depressurization test, and a heat exchanger leakage test. Almost a decade later, the Canadian General Standards Board published CAN/CGSB-51.71, titled “The Spillage Test” (later renamed “The Depressurization Test” in 2005) [27], to determine if air-moving devices (i.e., exhaust fans) in a dwelling impair normal venting of combustion appliances. A decade after the first release of the CAN/CGSB-51.71, ASTM International (formerly known as the American Society for Testing and Materials) published a guide (ASTM E1998) that provides four short-term (stress⁴⁰) test procedures and two procedures for assessing depressurization-induced backdrafting and spillage from vented combustion appliances [4]. CAN/CGSB-51.71 [27] and ASTM-E1998 [4] are the foundation for combustion safety diagnostics currently practiced by residential energy auditing institutions such as the Building Performance Institute (BPI) and the Residential Energy Services Network (RESNET) [6, 30]. The BPI and RESNET protocols include an induced-depressurization stress test for vented

⁴⁰ A “stress” test is one that uses instantaneous or short-term measurements under induced conditions and extrapolates results to predict performance under normal use. In particular, stress tests typically seek to induce “worst-case” conditions on a given day by operating all exhaust fans at their highest settings and opening or closing interior doors to achieve the highest level of depressurization in the occupiable area of the house containing the combustion appliance of interest.

appliances (no monitoring), a spillage and draft test, and an appliance carbon monoxide (CO) test.

The induced-depressurization “stress” test compares the maximum *fan-induced* depressurization of a house against prescribed limits, to estimate the potential for backdrafting and combustion spillage. For this test, both BPI and RESNET require that the Building Analyst Professional establish a “worst-case” depressurization where the appliance is located (known as the combustion appliance zone, or CAZ). This is done by turning on all of the exhaust fans, and configuring the interior doors to cause the maximum depressurization Δp_h of the CAZ relative to outdoors. Next, the baseline pressure of the CAZ (its pressure relative to outdoors when no ventilation fans are operating and all interior doors are open) is subtracted to yield a “worst-case” fan-induced pressure change, Δp_f :

$$\Delta p_f = \Delta p_{h\{fans_on\}} - \Delta p_{h\{fans_off\}} \quad (C1)$$

This “worst-case” fan-induced pressure change Δp_f is then compared to prescribed limits. Tables C1 and C2 provide a summary of the BPI and RESNET depressurization limits for various appliances and appliance configurations. If CAZ depressurization limits are exceeded under “worst-case” depressurization, then modifications to the home are required to reduce depressurization to acceptable limits.

Table C1: Building Performance Institute (BPI) [6] limits for fan-induced pressure change Δp_f in the combustion appliance zone (CAZ) of vented appliances.

Appliance Description	Maximum Δp_f [Pa]
Orphan ⁴¹ water heater	-2
Boiler or furnace common-vented with a water heater	-3
Boiler or furnace with a vent damper common-vented with a water heater	-5
Individual boiler, furnace, or domestic hot water heater	-5
Induced-draft boiler or furnace common-vented with a water heater	-5
Individual induced-draft boiler, furnace, or fan-assisted water heater	-15
Chimney-top draft inducer or direct-vented appliance or sealed combustion appliance	-50

In addition to measuring “worst-case” depressurization, both BPI and RESNET protocols require the building professional to conduct a spillage and draft test. This test is performed under “worst-case” depressurization, as well as under baseline conditions if the appliance fails under “worst-case” depressurization. To conduct the spillage and draft test, the appliance is

⁴¹ An “orphaned” water heater is one that is connected to a common vent that is no longer connected to a furnace. The common vent diameter, as such, is oversized for serving only the water heater.

turned on with a cold chimney and allowed to operate for a set amount of time (1 minute for BPI and 5 minutes for RESNET). If the appliance does not establish draft (combustion gas flow out of the house) after the set amount of time, the appliance fails. A smoke pen or mirror placed at the flue outlet (vent inlet) is used to determine if the appliance has established draft or if the appliance is spilling.

Table C2: RESNET [30] limits for Δp_f in the CAZ of vented appliances.

Appliance Description	Maximum Δp_f [Pa]
Oil Power Burner (fan-powered, oil burner); fan-assisted or induced-draft gas; solid-fuel burning appliance other than pellet stove with exhaust fan and sealed vents	-2
Atmospheric vented oil or gas system (Category I)	-5
Pellet stoves with exhaust fans and sealed vents	-15

After conducting the spillage and draft test, the building professional performs a CO test. The CO test is conducted when the appliance reaches a steady-state operating condition. Once steady-state operation is established, a probe from the combustion analyzer is placed in the appliance flue (prior to the draft diverter) and the CO concentration is measured. If the air-free CO in the flue exceeds 200 ppmv (100 ppmv as measured), then the appliance fails and should be repaired or replaced.

Research assessing the induced-depressurization stress test has broadly concluded that the tests are not reliable indicators of spillage potential, and are too conservative when predicting spillage (i.e., they predict more spillage than actually occurs) [5, 11, 17-19, 23, 29]. Most of the published literature [11, 18, 19] states that results from long term (at least one week) monitoring are more indicative of spillage events than the induced-depressurization stress test. However, even the one-week duration of monitoring that occurred in most of the published studies may be too short to reliably conclude that the studied appliances and houses will not have any incidences of spillage over the course of a typical year. Because extensive monitoring has not been conducted, the correlation between weather conditions, house depressurization, and combustion spillage remains unresolved.

Research investigating the correlation between combustion spillage and occupant health is also limited. Most research associated with combustion spillage focuses on CO, and neglects other hazards such as NO₂ and moisture-related problems [5, 11, 18, 19]. A more recent study, conducted by Wilson et al. in 1993 [37], found that the average indoor CO concentration in 286 California homes typically varied between 0.5 to 5 ppm. They also estimated that 95% of California homes had 48-hour average CO concentration less than 5.8 ppm and maximum 10-minute concentrations less than 18.6 ppm. Note that the data collected by Wilson et al. [37] include CO sources from attached garages and do not identify the contribution from combustion appliances alone.

A report investigating non-fire-related CO deaths associated with consumer products from 2007 [15] states that of the 169 CO related deaths (from 2007 to 2009) 2% were caused by water

heaters, 1% by ranges and ovens, 15% by furnaces, 4% by a wall or floor furnace, and 14% by other heating systems (i.e., portable, unvented heaters). Results from this consumer products report also suggest that acute CO poisoning from vented combustion appliances is extremely rare. However, more research is required to investigate both acute and chronic CO poisoning associated with vented combustion appliances.

To better assess the pollutant exposure risk associated with combustion spillage, the simulation studies presented in the following sections compare predicted concentrations of combustion by-products against published limits for *acute* CO and NO₂ exposure. Published limits for *chronic* CO and NO₂ exposure are not available. Table C3 lists the CO exposure limits that result in illness (hospitalization) or death. Table C4 lists the published limits for acute CO exposure set by various organizations. As shown in Table C4, many organizations disagree on the limit for acute CO exposure. Because the purpose of this study is to prevent events that could lead to exposure levels that result in hospitalization or death, most simulated results for CO are compared with the values listed in Table C3. For NO₂, simulated results are compared to acute limits shown in Table C5.

Table C3: Carbon monoxide (CO) exposures that could result in hospitalization or death [10].

Ambient Concentration [ppmv]	Exposure Time [h]	Symptoms
100	2–3	Slight headache
200	2–3	Headache, nausea
400	2–3	Life threatening
800	2	Death

C3 BOX MODEL

For simplicity, the three simulation studies conducted in this research adopt a box model approach for simulating a residence. The box model treats a building as a single well-mixed space. It assumes that any pollutant introduced to the space instantaneously mixes perfectly throughout the entire enclosed volume.

This section derives analytical solutions for the concentrations and exposures predicted by the box model, for a contaminant source inside a house such as a spilling combustion appliance. The resulting equations shed light on the factors that affect exposure to combustion gases, including the house volume, air change rate, and the rate at which the appliance emits combustion by-products.

Because the box model assumes instantaneous perfect mixing, there is uncertainty about the actual concentrations that could occur in the breathing zone. Under-estimates may result for occupants close to an emission source (since the model, contrary to reality, instantly dilutes emissions using the entire volume of air in the house). On the other hand, the model ignores details which may, in reality, act to reduce exposure. These include the immediate exhaust of

combustion appliance emissions, their containment in a smaller combustion appliance zone (CAZ), and stratification due to buoyancy.

Table C4: Carbon monoxide (CO) acute exposure limits.

Organization	Exposure Time [h]	Concentration [ppmv]
Consumer Product Safety Commission [25]	1	25
	8	15
U.S. National Ambient Air Quality Standards [33]	1	35
	8	9
California Air Quality Board [8]	1	35
	8	9
	8	6*
Health Canada [14]	1	25
	24	10

* Limit for high altitudes like Lake Tahoe.

Note: Limits for OSHA [34], NIOSH [34], and ACGIH [34] are 50 ppmv, 35 ppmv, and 25 ppmv, respectively, over an 8 hr period.

Table C5: Nitrogen dioxide (NO₂) published acute exposure limits.

Organization	Exposure Time [h]	Concentration [ppmv]
California Air Quality Board [8]	1	0.18
U.S. National Ambient Air Quality Standards [33]	1	0.10*

* 98th percentile, averaged over 3 years

Besides the combustion appliance itself, the most important variable is airflow across the building envelope. As stated in Section C1, the simulation studies take different approaches to estimating the airflows in and out of the residence. The spillage study is a scoping exercise that fixes the airflows based on field observations, while the airflow driver and yearly distribution studies use mechanistic airflow models to evaluate the effect of weather and some construction details. For simplicity, this section assumes that the airflows are known, and defers describing the airflow models to the appropriate sections.

C3.1 Indoor Concentration

To estimate indoor pollutant concentrations over time, we first write the differential equation that governs the rate of change of pollutant mass m in the box (the residence). Then, its time rate of change is:

$$\frac{dm}{dt} = -\lambda m + e \quad (C2)$$

where the loss rate, λ , represents loss mechanisms, such as airflow and deposition, that remove pollutant from the space; and the excitation rate, e , represents processes that add pollutant mass, for example an indoor source such as a spilling combustion appliance.

As indicated by Equation C2, losses tend to be proportional to the amount of pollutant currently in the air. For example, suppose the house has an air change rate a . Typically, a is measured in air changes per hour [h^{-1}]. For a house of volume V , this means a volume flow rate aV of air enters and leaves the house. Expressing the interior concentration, C , in units of mass per unit volume, e.g., in [$\mu\text{g}/\text{m}^3$], airflow removes pollutant mass from the house at a rate aVC . Since $m = VC$, airflow provides a loss term am . Similarly, deposition may be modeled as removing an airborne pollutant to room surfaces at a rate km , where again the deposition rate, k , has units of [h^{-1}]. Thus in Equation C2:

$$\lambda = a + k \quad (\text{C3})$$

The excitation rate in Equation C2 includes indoor sources and transport from the outdoors:

$$e = s + P(aVC_o) \quad (\text{C4})$$

where s is the rate at which pollutant mass is produced by indoor sources; C_o gives the concentration of pollutant outdoors; and the penetration efficiency, P , gives the fraction of the outdoor pollutant mass flow rate, aVC_o , that enters the space. The penetration efficiency accounts for filtration and deposition in the flow paths, and may range from 0 to 1.

Letting $m = VC$ in Equation C2, and normalizing the excitation rate by volume:

$$\sigma = \frac{e}{V} \quad (\text{C5})$$

gives an ordinary differential equation governing the concentration in the space:

$$\frac{dC}{dt} = -\lambda C + \sigma \quad (\text{C6})$$

Note that the steady-state solution, where $dC/dt = 0$, is:

$$C = \frac{\sigma}{\lambda} \quad (\text{C7})$$

As expected, increasing the source term, or decreasing the loss rate, drives the equilibrium indoor concentration higher.

For constant $\lambda > 0$ and constant $\sigma \geq 0$, the exact solution to Equation C6 can be written:

$$C\{t+h\} = \frac{\sigma}{\lambda} + \left(C\{t\} - \frac{\sigma}{\lambda} \right) e^{-\lambda h} \quad (\text{C8})$$

where $C\{t\}$ gives the concentration at time t . Thus, over time, the interior concentration rises or falls toward its steady-state value σ/λ .

The system *time constant* $1/\lambda$ provides a rough guide to the time needed to reach a new steady state. In Equation C8, note that the difference from steady state, $C\{t\} - \sigma/\lambda$, decreases by a factor

$e^{-\lambda h}$ over each time period h . If $h = 1/\lambda$, the difference from steady state gets reduced by $e^{-1} \approx 0.37$. Thus, three time constants ($3/\lambda$) bring the difference to about 5% of its new steady-state value.

C3.2 Exposure

The exposure, E , is defined as the integral of the indoor concentration over the time period of interest.

Integrating Equation C8, the exposure between time t and time $t + h$ for a constant σ is:

$$E_{t:t+h} = \frac{1}{\lambda} (\sigma h + C\{t\} - C\{t+h\}) \quad (C9)$$

for any period over which λ and σ remain constant.

If the source turns on and off over the exposure interval, σ is not constant and Equation C9 no longer holds. Suppose the source turns on at time $t = 0$, and runs at a constant mass rate s until $t = t_n$, when it turns off. In order to understand how such an intermittent source affects the long-term indoor air quality, we seek the total exposure over some period $0 \leq t \leq T$, where $T > t_n$. Appendix D derives an analytical solution, under the assumptions that: (1) only the source rate changes over the interval T ; and (2) the indoor concentration begins at equilibrium with the outdoors. This derivation yields:

$$E_{0:T} = \frac{aPC_oT}{\lambda} + \frac{st_n}{\lambda V} - \frac{s}{\lambda^2 V} (e^{\lambda t_n} - 1) e^{-\lambda T} \quad (C10)$$

The terms on the right side of Equation C10 can be interpreted as follows:

- In aPC_oT/λ , the product C_oT represents exposure, over the whole time period T , to the outdoor concentration. This exposure potentially is mitigated by two physical processes. First, if $P < 1$, the outdoor pollutant suffers losses in the flow paths, and the building envelope itself provides some protection. Second, note that $a/\lambda = a/(a+k) \leq 1$. If deposition to building surfaces is significant compared to the air change rate, then the building again reduces exposure to pollutants of outdoor origin.
- In $st_n = \lambda V$, the product st_n is the total mass of pollutant generated by the source. Dividing by V gives the well-mixed concentration that would result from an instantaneous release of that entire mass. Finally, dividing by λ gives the total exposure to such an instantaneous release over all time (i.e., in the limit as $t \rightarrow \infty$, not just through $t = T$).
- The final term reduces the exposure due to the indoor source to account for two effects: first, that the source releases its mass over $0 \leq t \leq t_n$, rather than instantaneously; and second, that the exposure ends at time T , rather than extending indefinitely. Note that since $e^{\lambda t_n} \geq 1$, this term can only reduce the computed exposure. Thus, the first two terms may be taken as a “worst-case” exposure (within the limitations of the box model).

C3.3 Limiting Long-Term Exposure

As shown in Table C4, exposure limits to CO typically are expressed in terms of the time-averaged concentration. Let $\langle C \rangle = E_{0:T} / T$ represent the average concentration between times 0 and T . From Equation C10, a source that turns off at $t_n < T$ produces an average concentration:

$$\langle C \rangle = \frac{aPC_o}{\lambda} + \frac{s}{V} \left(\frac{1}{\lambda T} \right) \left(t_n - \frac{1}{\lambda} [e^{\lambda t_n} - 1] e^{-\lambda T} \right) \quad (C11)$$

Thus the time-averaged indoor concentration is the sum of contributions from outdoor and indoor sources (in the first and second terms, respectively). In Equation C11:

- The contribution due to outdoor sources is always less than or equal to C_o . Penetration losses ($P < 1$) and indoor deposition ($k > 0$, which makes $a/\lambda < 1$) reduce the ability of outdoor sources to affect indoor exposure.
- Increasing the air change rate, and hence $\lambda = a + k$, always tends to bring the indoor average concentration closer to the effective outdoor concentration, PC_o .
- The indoor source's contribution to $\langle C \rangle$ is almost inversely proportional to the loss rate. If $C_o = 0$ and $k = 0$, this means the average indoor concentration is nearly inversely proportional to the air change rate. Deposition, of course, only improves indoor air quality.
- The indoor source's contribution to the average concentration is directly proportional to the source mass rate s .
- Lacking significant outdoor contributions, $\langle C \rangle$ is inversely proportional to the house volume V .
- Lacking significant outdoor contributions, the average concentration is nearly proportional to the length of time the source is on (or, equivalently, to the total emission rate st_n).
- In all the effects for which $\langle C \rangle$ is nearly proportional to a design parameter, a longer averaging interval T makes the relationship more nearly proportional (a similar statement holds for the inversely proportional relationships as well).

As with Equation C10, the term $e^{-\lambda T}$ can only decrease the estimated average concentration. Therefore, the reduced expression:

$$\langle C \rangle = \frac{aPC_o}{\lambda} + \frac{st_n}{\lambda VT} \quad (C12)$$

gives a “worst-case” long-term average concentration. Again, this statement must be considered within the limitations of the underlying model. Recall that, in addition to the well-mixed assumption behind the box model, Equation C10 treats the air change rate a as constant over the entire integration period T , and assumes that, before the source turns on, the indoor air is at equilibrium with the outdoor concentration. For an eight-hour average concentration in a real

house, these idealizations are not likely to hold. Nevertheless, the resulting expressions show broadly how the key variables interact.

C3.4 Limiting Short-Term Exposure

Some applications demand a shorter exposure window than the long-term average of Equation C11. For example, Table C4 includes short-term limits of duration $T = 1$ h. For such applications, suppose the exposure measurement starts at time $t_b > 0$, and runs through $t_b + T$. If this exposure window ends before t_n , or starts after t_n , then the source is constant over the window, and Equation C9 gives the exposure.

If, on the other hand, the source turns off during the exposure window, then the exposure calculation closely follows the derivation of Equation C10. Suppose $0 \leq t_b \leq t_n \leq (t_b + T)$. As before, an indoor source of strength s turns on at $t = 0$ and off at $t = t_n$. Again assume that $a > 0$, $k \geq 0$, and $C_o \geq 0$ are constant, and that the indoor concentration initially is in equilibrium with the outdoors. Then one can show that:

$$E_{t_b, t_b+T} = \frac{aPC_oT}{\lambda} + \frac{s(t_n - t_b)}{\lambda V} + \frac{s}{\lambda^2 V} (1 - e^{-\lambda t_b}) - \frac{s}{\lambda^2 V} (e^{\lambda t_n} - 1) e^{-\lambda(t_b+T)} \quad (C13)$$

Compared to Equation C10, the mass contribution st_n from the indoor source decreases to $s(t_n - t_b)$. This reflects the fact that the exposure window encompasses less of the time during which the source is on. However, the source already has been on for a time t_b before the exposure window begins, and some of the released pollutant mass remains indoors at time t_b . Therefore the product $s(t_n - t_b)$ under-estimates the pollutant mass that contributes to the exposure. The third term in Equation C13, which does not appear at all in Equation C10, accounts for this additional mass. Of course, setting $t_b = 0$ recovers Equation C10.

To find the start time t_b that maximizes the exposure over a fixed duration T , set $dE/dt_b = 0$ for Equation C13. This yields:

$$t_b = \frac{\ln \left\{ 1 + (e^{\lambda t_n} - 1) e^{-\lambda T} \right\}}{\lambda} \quad (C14)$$

Note in the limit as $T \rightarrow 0$, $t_b \rightarrow t_n$. In other words, narrowing the exposure window pushes the period of maximum exposure towards the point of peak indoor concentration, just when the indoor source turns off. Conversely, as $T \rightarrow 1$, $t_b \rightarrow 0$. That is, widening the exposure window causes the period of maximum exposure to start closer to the time the source turns on. In all cases, the maximum exposure of duration T occurs for a period that starts between $t = 0$ and t_n , and ends after t_n .

C4 THE SPILLAGE STUDY

As stated in Section C1, current combustion safety protocols do not assess the health risk from intermittent and prolonged spillage events. Additionally, the protocols do not evaluate the effect of depressurization and house characteristics (i.e., air tightness and volume) on indoor pollutant concentrations. In order to evaluate how these and other parameters affect indoor air

quality, we simulated pollutant concentrations when varying house volume, house tightness, depressurization, appliance size, appliance emission concentrations, and spillage duration. The simulation implements the simple box model, described in Section C3, assuming practical values for the air change rate, indoor source rate, and other parameters. The spillage is divided into four subsections: (1) assumptions for determining the air change rate; (2) calculations for predicting the appliance emission rate; (3) general simulation assumptions; and (4) results.

C4.1 Air Change Rate

In order to determine the air change rate, a , the spillage study assumes the house's air change rate at 50 Pa depressurization, a_{50} , is known. Using a_{50} , the corresponding volume airflow at 50 Pa is:

$$Q_{50} = a_{50}V \quad (C15)$$

where Q_{50} has units [m³/h]. Assuming the leakage paths through the house envelope are lumped together, the standard power law relation can be used to relate volume airflow and depressurization:

$$Q = C_f (\Delta p)^n \quad (C16)$$

where the flow coefficient, C_f , and the pressure exponent, n , are experimentally-determined constants [36]. In Equation C16, the simulation uses $n = 0.65$, which is common general assumption for mixed paths. Additionally, the pressure drop through the flow path, Δp , is taken as the absolute value of the house pressure relative to outdoors, Δp_h . Estimating C_f using Q_{50} and substituting the solution into Equation C16 gives:

$$Q = Q_{50} \left(\frac{\Delta p}{50} \right)^n \quad (C17)$$

and an air exchange rate of:

$$a = a_{50} \left(\frac{\Delta p}{50} \right)^n \quad (C18)$$

C4.2 Emission Source Mass Flow Rate

The mass flow rate of emissions from the appliance, s , depends on the mass flow rate of the combustion exhaust and the concentration in that exhaust. The mass flow rate of the exhaust is the sum of the mass flow rate of the fuel into the appliance, \dot{m}_f , and the mass flow rate of required combustion air, \dot{m}_a :

$$\dot{m}_{ex} = \dot{m}_f + \dot{m}_a \quad (C19)$$

The mass flow rate of fuel into the appliance in units of [kg/h] is:

$$\dot{m}_f = \frac{BR}{HHV} \rho_f \quad (C20)$$

In Equation C20, BR is the appliance burner rating in [MJ/h], ρ_f is the fuel density in [kg/m³], and HHV is the higher heating value of the fuel in [MJ/m³]. The higher heating value of the fuel, HHV, is the amount of heat produced by combusting a unit quantity of fuel and allowing the products to cool to room temperature (thus accounting for the latent heat of vaporization of the water in the combustion products). The simulation calculates fuel density using the specific gravity of the fuel and the density of air at normal temperature and pressure (NTP), i.e., at 60°F and 1 atm.

The mass flow rate of required combustion air is:

$$\dot{m}_a = \dot{m}_f \times AFR_{st} \quad (C21)$$

where AFR_{st} is the stoichiometric air-fuel ratio by mass (~16:5 for natural gas or ~17:2 for methane).

Using the total mass flow rate of the exhaust, the mass flow rate of a given pollutant from the combustion appliance is:

$$s = \dot{m}_{ex} \left(\frac{\rho_{pol}}{\rho_{ex}} \right) \left(\frac{C_{ex}}{10^6} \right) \left(\frac{10^9 \mu g}{kg} \right) \quad (C22)$$

where ρ_{pol} is the density of the pollutant [kg/m³]; ρ_{ex} is the density of the exhaust gases [kg/m³]; and C_{ex} is the air-free measurement of the pollutant [ppmv]. The final constant factor converts the source rate from [kg/h] to the desired units, [μ g/h]. As above, \dot{m}_{ex} is in [kg/h]. Equation C22 can be simplified further by applying the ideal gas law, converting the ratio of densities to a ratio of molar masses, assuming the exhaust gases and the pollutant of interest are at the same temperature and pressure, and that the molar mass of the exhaust gases is equal to the molar mass of air. This gives:

$$s = \dot{m}_{ex} \left(\frac{M_{pol}}{M_{air}} \right) C_{ex} \times 1000 \quad (C23)$$

where M_{pol} is the molar mass of the pollutant [kg/kmol] and M_{air} is the molar mass of air (28.97 kg/kmol).

C4.3 Simulation Assumptions

All simulated houses have an interior height of 8 feet. Most simulations assume the house floor area is 1200 ft², which is the average size for a small house (<1800 ft²) in California [16]. The simulations focus on smaller houses because they accumulate pollutant concentrations faster than larger houses of equal tightness, increasing the risk of high pollutant exposures. The appliance has a burner rating of 40,000 Btu/h, which represents a small central furnace, a large wall furnace, or a common size (31 to 49 gallon) for a water heater in residential buildings [12, 35]. One can scale the simulation results to homes and appliances of different sizes. As shown in Section C3, in the absence of significant outdoor concentration, the indoor pollutant concentration is inversely proportional to house volume and directly proportional to the source

mass rate. Because s is directly proportional to burner size, indoor pollutant concentrations are also directly proportional to burner size. Most of the simulations assume a house tightness of $a_{50} = 4 \text{ h}^{-1}$, representing the mean tightness of a California home after being retrofit [9]. The simulations explore the effect of a_{50} on indoor pollutant concentrations at a fixed depressurization. The air change rate, a , was calculated using Equation C18, assuming fan-induced house depressurizations of $\Delta p_h = -2, -5$, and -15 Pa . These depressurization values correspond to the fan-induced pressure change limits set by BPI [6] and RESNET [30] (see Tables C1 and C2) assuming a baseline pressure, $\Delta p_{h(fans_off)}$, of 0 Pa . The simulations assume the house maintains a *constant* depressurization (and therefore a constant air change rate) when the appliance is operating (i.e., spilling) and when the appliance is off (i.e., no longer spilling).

The simulations predict *changes* in indoor CO and NO₂ concentrations resulting from appliance operation. The simulations do not include pollutant contributions from other sources (e.g., outdoors), and assume the initial interior concentration is zero ($C\{0\} = 0$). The deposition rate, k , is 0 h^{-1} for CO, and 0.5 h^{-1} for NO₂. These deposition rates are conservative estimates, based on measurements in residences [24]. For CO, the simulations assume the combustion appliance spills air-free CO at emission rates of $C_{ex} = 200, 400$, and 1200 ppmv . The air-free CO emission rates are based on the BPI and RESNET flue air-free CO limits (200 ppmv) [6, 30], the ANSI flue air-free CO limits for furnaces and water heaters (400 ppmv) [2], and a limit indicative of a malfunctioning appliance that exceeds the BPI, RESNET, and ANSI air-free CO limits (1200 ppmv). The simulations also predict the appliance flue-gas concentrations required to exceed acute CO limits shown in Table C4. For indoor NO₂, the simulations predict appliance flue-gas concentrations required to exceed acute NO₂ limits shown in Table C5.

Exposure limits for CO and NO₂ are frequently published in units of [ppmv]. Because C is a function of s , which has units [$\mu\text{g}/\text{h}$], then C will have units of [$\mu\text{g}/\text{m}^3$], assuming the volume of the house is in [m^3]. In order to provide results that can be directly compared with published exposure limits, the indoor concentrations determined from the simulations are converted from [$\mu\text{g}/\text{m}^3$] to [ppmv] using:

$$C[\text{ppmv}] = C\left[\frac{\mu\text{g}}{\text{m}^3}\right] \div \left(\rho_{pol}\left[\frac{\text{kg}}{\text{m}^3}\right] \times 1000\left[\frac{\text{g}}{\text{kg}}\right]\right) \\ = C\left[\frac{\mu\text{g}}{\text{m}^3}\right] \div \left(\frac{P_{pol}[\text{kPa}] \cdot M_{pol}\left[\frac{\text{kg}}{\text{kmol}}\right]}{R_u\left[\frac{\text{m}^3 \times \text{kPa}}{\text{kmol} \times \text{K}}\right] \cdot T_{pol}[\text{K}]} \times 1000\left[\frac{\text{g}}{\text{kg}}\right]\right) \quad (\text{C24})$$

where P_{pol} is the pressure at which the pollutant is measured, T_{pol} is the temperature at which the pollutant is measured, and R_u is the universal gas constant. The simulations in this study assume an indoor pressure of 101 kPa (14.73 psia) and an indoor temperature of 288.7 K (60°F). Applying these conditions to Equation C24 yields:

$$C[\text{ppmv}] = 2.3765 \times 10^{-2} \left[\frac{\text{m}^3 \times \text{kg}}{\text{g} \times \text{kmol}} \right] \left(\frac{C \left[\frac{\mu\text{g}}{\text{m}^3} \right]}{M_{pol} \left[\frac{\text{kg}}{\text{kmol}} \right]} \right) \quad (\text{C25})$$

C4.4 Results for the Spillage Study

To assess the risk of pollutant exposure from combustion spillage, we first determined the indoor CO threshold using combustion safety test conditions set by BPI and RESNET, as described in Section C2. Using these test conditions, the simulation predicts changes in indoor CO concentrations from short spillage events (5 minutes) and short, cycling spillage events (5 minutes every hour for 24 hours). Next, we investigated the effects of prolonged spillage from water heaters and furnaces. In these first two sets of simulations, CO is the primary focus because occupant death or hospitalization from CO is the largest concern for building professionals.

After assessing current protocols and investigating short and prolonged spillage events, we use the simulations to help guide development of new combustion safety protocols by investigating the effects of depressurization and house tightness (i.e., a_{50}) on indoor CO concentrations. We also use the simulations to predict the flue-gas concentrations needed for indoor concentrations to exceed published limits, and expand the results to include CO and NO₂. The purpose of this last simulation is to demonstrate how the calculations can be used as a screening tool for assessing risk from CO and NO₂.

C4.4.1 Effects of Short Spillage Events

To estimate the risk associated with CO due to single and cyclic short spillage events, we simulated a 40,000 Btu/h appliance spilling CO once for 5 minutes, and spilling CO the first 5 minutes of every hour over the course of a day. As described in Section C2, combustion protocols require that a natural draft appliance establish draft within 1 to 5 minutes and emit no more than 200 ppmv of air-free CO. However, the protocols are unclear on how frequently an appliance is allowed to spill over a given time period. Therefore, we assumed the protocols allowed a short duration of spillage every hour over the course of a day. Both the single and cyclic spillage simulations assumed the appliance spills 200 ppmv air-free CO, the concentration permitted by combustion protocols, and 1200 ppmv air-free CO, a concentration indicative of a malfunctioning appliance.

The minimum ventilation requirement from ASHRAE 62.2 [3] is 0.25 h⁻¹ for the 1200 ft² house and 0.20 h⁻¹ for the 3000 ft² house. These minimum ventilation requirements include the infiltration credit assuming the house has one bedroom and an average weather factor of 0.6. For the simulated houses, the minimum ASHRAE ventilation requirement with the infiltration credit is approximately equal to, or is more than, the air exchange rate of the house at -2 Pa depressurization. Therefore, the simulation assumed an air exchange rate resulting from -2 Pa depressurization during and after spillage.

The predicted indoor CO concentrations from a single, 5 minute spillage event are shown in Table C6. For this simulation, the tightness and size of the house were varied while the depressurization was kept constant at -2 Pa (the lowest allowable depressurization limit for a combustion appliance). The simulated results provide an example of a combination of conditions that could lead to potentially hazardous conditions.

Table C6: Predicted indoor carbon monoxide concentrations after a 40,000 Btu/h appliance spills 200 ppmv and 1200 ppmv of air-free CO for 5 minutes in a house that is depressurized to -2 Pa.

House Size [ft ²]	ACH ₅₀ [h ⁻¹]	ACH at -2 Pa [h ⁻¹]	Flue air-free CO Concentration [ppmv]	Indoor CO Concentration at 5 minutes [ppmv]	Indoor CO Concentration at 1 hour [ppmv]
1200	2	0.25	200	0.7	0.5
			1200	4.0	3.2
	4	0.49	200	0.7	0.4
			1200	4.0	2.5
	8	0.99	200	0.7	0.3
			1200	3.9	1.6
3000	2	0.25	200	0.3	0.2
			1200	1.6	1.3
	4	0.49	200	0.3	0.2
			1200	1.6	1.0
	8	0.99	200	0.3	0.1
			1200	1.6	0.6

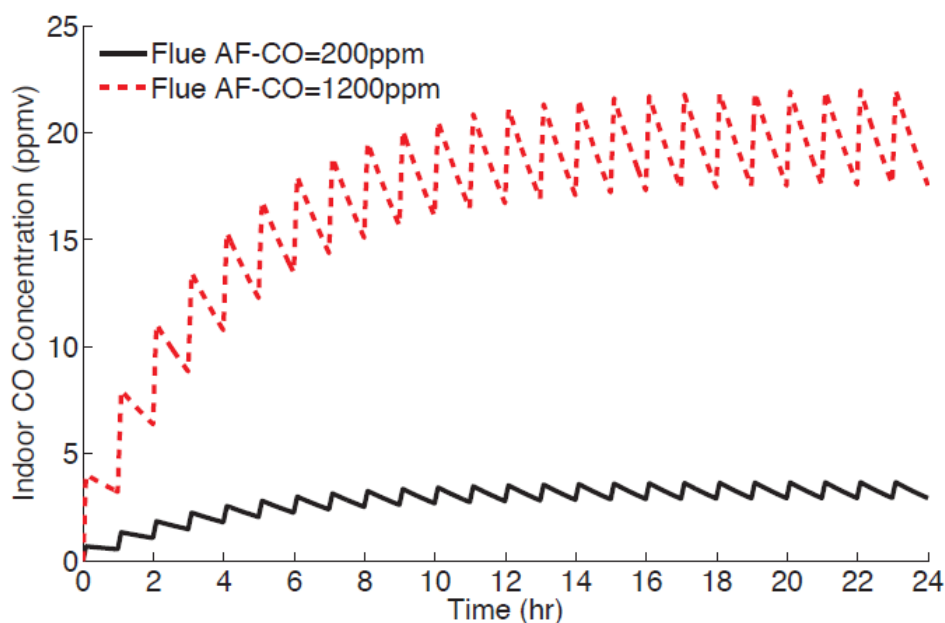
For short spillage, the peak indoor concentration is almost unaffected by the house tightness (since 5 minutes of spillage is short compared to the time scale $1/a$ at which air flushes out the house). Although the indoor concentrations are significantly below the CO hospitalization and death thresholds listed in Table C4, some of the conditions could lead to chronic exposure. For example, 5 minutes of spillage from an appliance emitting high (1200 ppmv) CO exhaust gas in a small house can create indoor concentrations (4 ppmv) that would be of concern for chronic exposure. In a small, tight home with $a_{50} = 2 \text{ h}^{-1}$, the risk of chronic exposure increases because the indoor concentrations remain high without extra mechanical ventilation, as indicated by the indoor CO concentration after 1 hour. In this 1200 ft² home, a building professional may want to ensure that the appliance burner is clean and functioning properly, the air-free CO concentration is much lower than 200 ppmv limit, and the appliance starts drafting sooner (e.g., 1 minute vs. 5 minutes). Increasing the safety measures for a small house will reduce the risk that the occupants will be exposed to unhealthy levels of CO.

In a larger house, the results in Table C6 show that a single short spillage event does not present a risk when the appliance is spilling low or high concentrations of CO. Increasing the house size from 1200 ft² to 3000 ft² under the same spilling and house conditions decreases the indoor CO

concentration by 60%. Most of the predicted indoor concentrations for the larger house are below the measurement threshold of many hand-held combustion analyzers. These results indicate that the combustion protocols may establish limits that are too conservative for single, short spillage events in larger homes.

Unlike single spillage events, cyclic spills can increase indoor CO concentration to hazardous levels for all home sizes. As shown in Figure C1, the maximum indoor CO concentrations from a 40,000 Btu/h appliance spilling the first 5 minutes of every hour over the course of a day (24 hours) is about 5.5 times higher than the indoor CO concentration from 5 minutes of spillage. Additionally, the indoor concentrations reach a dynamic steady-state after a 24-hour period of cyclic spillage. The simulated results in Figure C1 assume the appliance spills 200 ppmv and 1200 ppmv of air-free CO in a 1200 ft² house that is depressurized to -2 Pa (0.25 h⁻¹) and has a tightness of $a_{50} = 2 \text{ h}^{-1}$. The small, tight house from the previous simulation was chosen to maximize the indoor CO concentration.

Figure C1: Simulated changes in indoor CO concentrations assuming a 40,000 Btu/h appliance is spilling 200 ppmv or 1200 ppmv of air-free CO (AF-CO) the first 5 minutes of every hour over the course of a day. The appliance is located in a 1200 ft² house that is depressurized to -2 Pa ($a = 0.25 \text{ h}^{-1}$) and has a tightness of $a_{50} = 2 \text{ h}^{-1}$.



Although Figure C1 shows that indoor concentrations from cycling spillage are well short of acutely dangerous levels (see Table C3), indoor concentrations over time could reach levels of concern. For example, the maximum 8 hour average (and 1 hour average) indoor concentrations from an appliance spilling 200 ppmv air-free CO cyclically through the day is about 3 ppmv, a level that could be of concern for chronic exposure, but that is well below acute exposures. If the appliance malfunctions and spills 1200 ppmv air-free CO cyclically through the day, the maximum 8 hour average (and 1 hour average) indoor concentrations is about 20 ppmv, a level that exceeds acute exposures. Similar to the single short spillage events, doubling the house size decreases the indoor CO concentrations by half. The results from the cycling spillage events

indicate that the combustion safety protocols are protective against deadly acute CO conditions, even in the case when the appliance is malfunctioning and has repeated intermittent spillage.

Nevertheless, the test protocols may be too conservative for larger homes, or for houses with infrequent spills. For example, homes just below the passing level can incur significantly higher costs due to repairs that have a minimal impact for improving health. In fact, some homes that fail combustion safety protocols may not be hazardous, as indicated by the results for a 3000 ft² house. The purpose of this short term study is not to indicate that high concentrations of air-free CO emitting from an appliance are acceptable; instead, the purpose is to show that the combustion safety protocols should take into account the house size and statistical variations (i.e., occupant behavior and weather) associated with appliance spillage in order to appropriately assess and mitigate risk. Regardless of house size and statistical variations, the building professional should continue to make sure that the appliance burner is clean and functioning properly (flue air-free CO less than 200 ppmv), and that the appliance establishes draft quickly.

C4.4.2 Effects of Prolonged Spillage Events

Compared to short spillage events, prolonged spills increase the risk of producing indoor CO concentrations that could result in hospitalization or death. To assess this risk, we simulated extended spillage from a water heater, and continuous spillage from a furnace, assuming the appliances are operating independently. Both simulations assume a house tightness of $a_{50} = 4 \text{ h}^{-1}$, representing the mean tightness of a California home after retrofit [9].

For the water heater simulation, we used monitored data from 143 California homes collected by Mullen et al. [22] to determine the maximum water heater on-time over 1, 4, and 8 hour intervals. These data show that the 95th percentile of maximum on-time is 59 minutes in a 1 hour period, 105 minutes in a 4 hour period, and 139 minutes in an 8 hour period. The simulation incorporates these data by calculating the indoor CO concentration when the water heater spills for the maximum on-time in each time period. Additionally, the simulation assumes the house is depressurized to -2 Pa, the minimum fan-induced pressure change published in combustion safety protocols for water heaters [6].

Table C7 shows simulated indoor CO concentrations assuming a water heater spills 200 ppmv, 400 ppmv, or 1200 ppmv of air-free CO. When the water heater spills 200 ppmv or 400 ppmv of air-free CO, the indoor CO concentrations for each operating time do not exceed the published 1 hour limits in Table C4. When the water heater spills 400 ppmv of air-free CO, the average 8 hour indoor CO concentration just reaches the California Air Quality Board and NAAQS 8 hour limits [8, 33]. The indoor concentrations reach potentially harmful levels when the water heater spills 1200 ppmv of air-free CO, but still remain below indoor CO limits that could result in a life-safety hazard (see Table C3).

In the event that the house is no longer depressurized when the water heater stops operating and exchanges air at a very low rate, the removal of indoor pollutants will take longer than if the house was depressurized. For example, in the case where the water heater spills 400 ppmv of air-free CO for 139 minutes in an 8 hour period, the indoor CO concentration would be closer

to the maximum value of 22.5 ppmv at the end of 8 hours, rather than 1.4 ppmv. These results suggest that if a water heater spills high concentrations of CO, the indoor CO concentrations could maintain a level that would be an acute hazard if the house were no longer depressurized. However, if the water heater spills less than 400 ppmv of air-free CO, the indoor CO concentrations could present a chronic health hazard, but not a life-safety hazard.

Table C7: Simulated indoor CO concentrations assuming a 40,000 Btu/h water heater spills 200 ppmv, 400 ppmv, or 1200 ppmv of air-free CO (AF-CO) in a 1200 ft² house. The house is depressurized to -2 Pa ($a = 0.49 \text{ h}^{-1}$), and has a tightness of $a_{50} = 4 \text{ h}^{-1}$. Operation times represent the 95th percentile of maximum on-time in 143 California homes [22].

Time Period [h]	On-Time [min]	Flue AF-CO [ppmv]	Maximum Indoor CO [ppmv]	Max 1 hour Avg Indoor CO [ppmv]	8 hour Avg* Indoor CO [ppmv]	Indoor CO at End of Time Period [ppmv]
1	59	200	6.3	3.5	N/A	6.3
		400	12.7	7.1	N/A	12.6
		1200	38.1	21.2	N/A	37.7
4	105	200	9.5	8.5	N/A	3.1
		400	19.1	17.1	N/A	6.3
		1200	57.2	51.2	N/A	18.9
8	139	200	11.2	10.3	4.6	0.7
		400	22.5	20.6	9.2	1.4
		1200	67.4	61.8	27.6	4.1

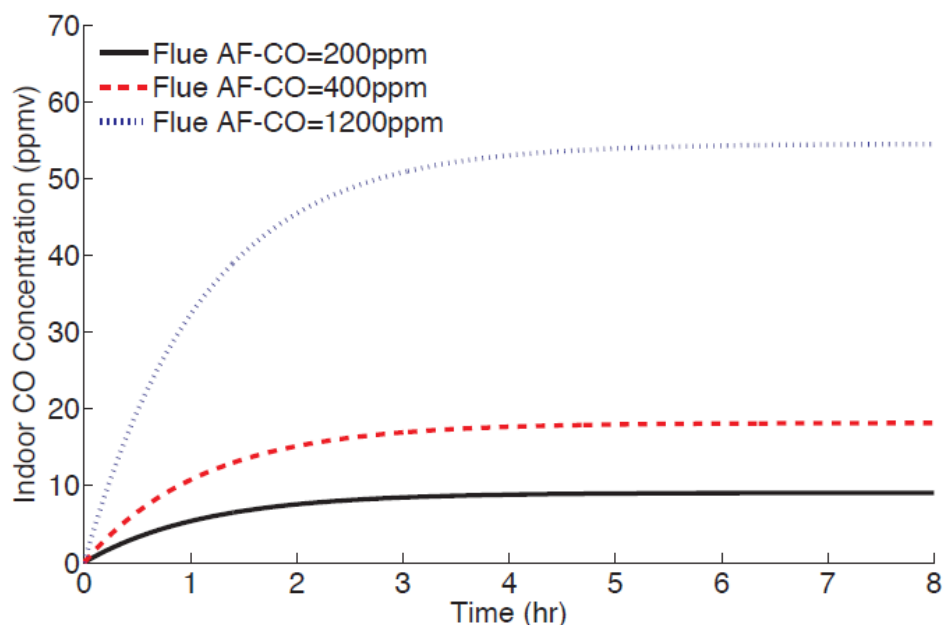
*8-hour average indoor concentrations are not applicable (N/A) for simulation time periods less than 8 hours.

Unlike water heaters, furnaces (especially undersized ones) may sometimes operate continuously throughout a day, thus increasing the health risk. To assess the potential risk from furnaces, the simulation assumes a 40,000 Btu/h furnace (a common size for a small central furnace or large wall furnace) that spills continuously for 8 hours. The simulation also assumes the house is depressurized continuously to -5 Pa, the minimum fan-induced pressure change published in combustion safety protocols for furnaces [6, 30]. For both the water heater and the furnace simulations, the chosen depressurizations assume the minimum ventilation (worst-case for indoor pollutant accumulation) allowed by the combustion protocols for each type of appliance.

Figure C2 shows the simulated indoor CO concentrations assuming the furnace spills 200, 400, or 1200 ppmv of air-free CO. When the furnace spills 200 ppmv of air-free CO, the indoor CO concentrations do not reach acute hazards as they are below the published limits in Table C4. When the furnace spills 400 ppmv of air-free CO, the indoor CO concentrations are still not life threatening, but do exceed the 8 hour limits, thus presenting an acute hazard. Note that the steady-state indoor CO concentrations for the furnace spilling at -5 Pa depressurization (55 ppmv) are almost the same as the maximum indoor concentrations resulting from 105 min of water heater spillage at -2 Pa depressurization (57 ppmv). This indicates that the steady-state

concentrations at a higher air exchange rate may provide an alternative method for predicting risk from shorter durations of spillage at a lower air exchange rate.

Figure C2: Simulated changes in indoor CO concentrations assuming a 40,000 Btu/h furnace spills 200, 400, or 1200 ppmv of air-free CO (AF-CO) continuously for 8 hours. The furnace is located in a 1200 ft² house that is depressurized to -5 Pa ($a = 0.90 \text{ h}^{-1}$) and has a tightness of $a_{50} = 4 \text{ h}^{-1}$.



The furnace simulations also show that at 8 hours, indoor concentrations have reached steady-state and after 4 hours, the indoor CO concentrations are within 3% of the steady-state value. These results indicate that the steady-state indoor CO concentrations provide a good approximation of the indoor CO concentrations from a furnace spilling continuously. Similar to the water heater results, the furnace simulation results indicate that even in a situation where an appliance is continuously spilling in a moderately airtight home, an acute hazard only arises if the burner is malfunctioning. Therefore, combustion safety protocols should ensure that conditions of sustained spillage and high emissions do not exist without high ventilation.

C4.4.3 Initial Steps Towards Developing New Combustion Safety Protocols

The furnace and water heater results show that acute hazards often require a combination of problems, but that the risk depends on the house configuration. In a moderately tight home (4 ACH₅₀), prolonged spillage, a malfunctioning appliance, and low ventilation are needed to create an acute hazard. However, in a very tight house (2 ACH₅₀), prolonged spillage and a malfunctioning appliance may be enough to create a life-threatening situation. To further assess the risk of tightening homes, we next predicted the flue-gas concentrations required to reach hazardous indoor pollutant concentrations for specific house configurations. The purpose of these simulations is to provide building professionals a tool for quickly assessing the risk of a catastrophic event after tightening, assuming a given combination of appliance characteristics and house depressurization. This information helps to identify high- and low-risk homes after tightening by predicting the flue-gas concentration leading to hazardous indoor concentrations.

The simulations in this section predict steady-state indoor CO concentrations to assess risk from spillage. As shown in Section C4.4.1, indoor concentrations from short spillage events are unlikely to result in acute hazards, even when the appliance is malfunctioning. Section C4.4.2 shows that the steady-state indoor concentrations from a furnace spilling at a higher ventilation rate (corresponding to a depressurization of -5 Pa) produced almost the same indoor concentrations as a water heater spilling for about two-hours at a lower ventilation rate (corresponding to a depressurization of -2 Pa). Therefore, the indoor concentrations from prolonged spillage events were determined using the steady-state concentrations for both water heaters and furnaces. The simulated house is 1200 ft² with air tightnesses of $a_{50} = 2$ and 4 h⁻¹. House depressurizations of $\Delta p = -2$ Pa and -5 Pa were simulated to match BPI and RESNET protocols.

The effects of depressurization on indoor pollutant concentrations are shown in Figure C3. The simulated results show that the indoor CO concentration decreases substantially with increasing depressurization. These results are expected because increasing depressurization increases the ventilation rate and thus increases the indoor pollutant removal rate. The results also agree well with the ASTM E1998 [4] statement that an appliance emitting 400 ppmv of air free CO is unlikely to produce indoor concentrations exceeding 100 ppmv. Even for a very tight house with $a_{50} = 2$ h⁻¹ with a low depressurization (-2 Pa), the steady-state indoor CO concentration are below life-threatening levels (68 ppmv).

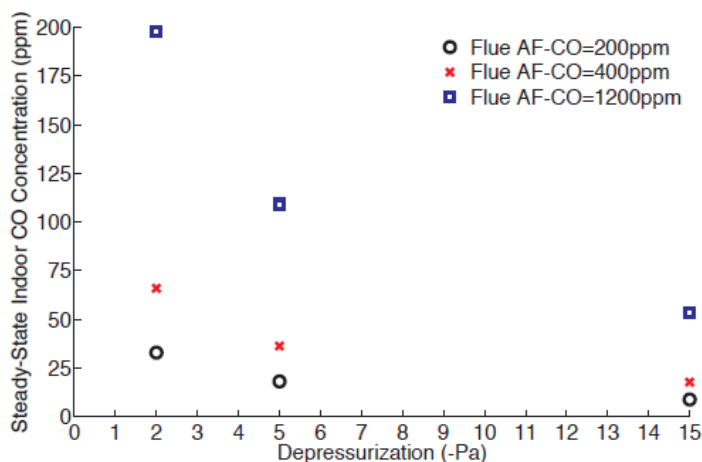
Figure C3 also shows that for a fixed depressurization, the steady-state CO concentration indoors is inversely proportional to a_{50} . For example, a home with $a_{50} = 4$ h⁻¹ (Figure C3b) and an appliance spilling 1200 ppmv of air-free CO at a depressurization of -2 Pa yields a steady-state indoor concentration of about 100 ppmv. Halving the air tightness to $a_{50} = 2$ h⁻¹ (Figure C3a) under the same conditions doubles the indoor concentration, to about 200 ppmv. Equation C18 also shows that the air change rate is proportional to a_{50} , and from Equation C7, in the absence of significant outdoor concentrations, the steady-state indoor concentration is inversely proportional to the air change rate.

The effects of air tightness (a_{50}) on indoor pollutant concentrations are shown in Figure C4. The results show that increasing air tightness increases indoor pollutant concentrations. Although Figure C4 shows trends similar to Figure C3, Figure C4 provides a different method of understanding the relationship between air tightness, depressurization, and indoor concentration. Combining the results from Figures C3 and C4 can assist with assessing the risk of a catastrophic event occurring if the house is tightened, but the appliance and exhaust fans (or corresponding depressurization) remain the same.

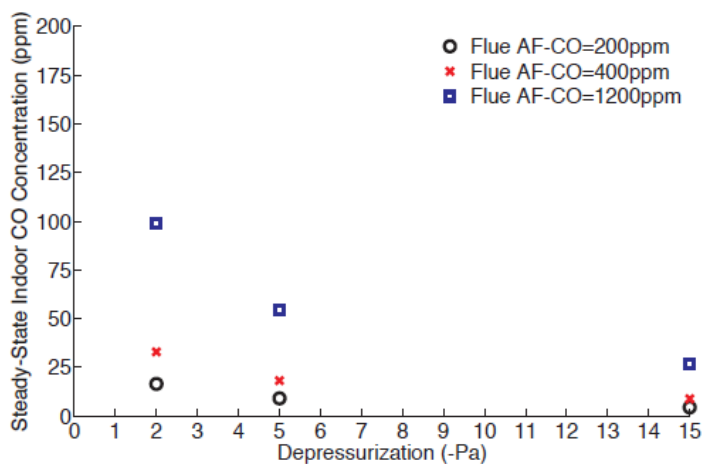
To develop a screening tool for identifying the risk of a catastrophic event, one could use the simulation results to predict the flue-gas concentrations required to reach hazardous indoor pollutant concentrations for specific house configurations. This simulation includes the predicted CO and NO₂ flue-gas concentrations required to reach thresholds published in Tables C4 and C5. As stated previously, the steady-state indoor concentrations were chosen to assess risk from prolonged spillage of a furnace or a water heater. Figure C5 shows the simulated results for the flue-gas air-free CO required to reach steady-state indoor CO concentrations of 9 ppmv, 25 ppmv, or 100 ppmv at various house depressurizations. For the 9 ppmv threshold, the

flue-gas air-free CO concentrations must be less than 110 ppmv, especially for a natural draft water heater that spills continuously at -2 Pa depressurization. A natural draft furnace or water heater spilling at -5 Pa depressurization must have a flue-gas air-free CO concentrations less than 200 ppmv in order to remain below the 9 ppmv threshold. Although the 9 ppmv threshold may not be life-threatening, it could be a hazard for sensitive individuals.

Figure C3: Simulated indoor CO concentrations with varying depressurization assuming a 40,000 Btu/h appliance is spilling continuously in a 1200 ft² house with a tightness of (a) $a_{50} = 2 \text{ h}^{-1}$ and (b) 4 h^{-1} .

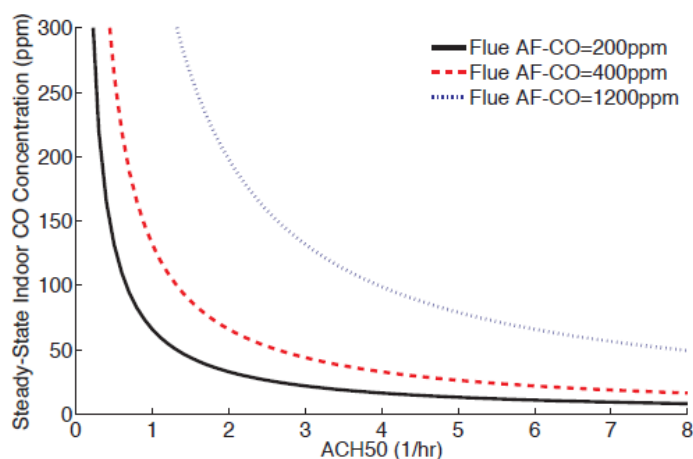


(a) $a_{50} = 2 \text{ hr}^{-1}$

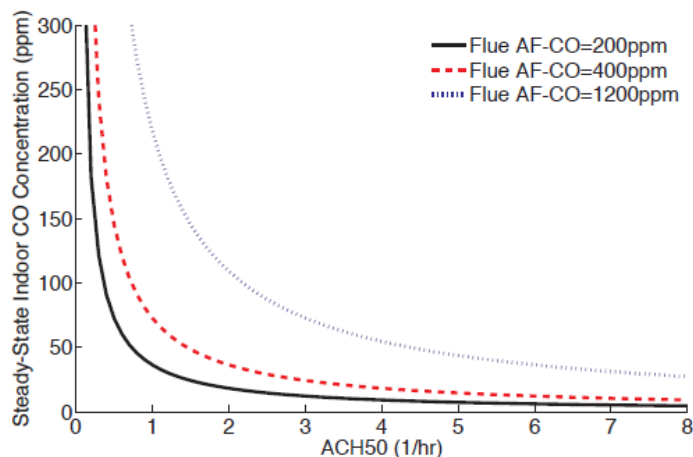


(b) $a_{50} = 4 \text{ hr}^{-1}$

Figure C4: Simulated indoor CO concentrations with varying a50 assuming a 40,000 Btu/h appliance is spilling continuously in a 1200 ft² house under depressurizations of -2 Pa (a) and -5 Pa (b).



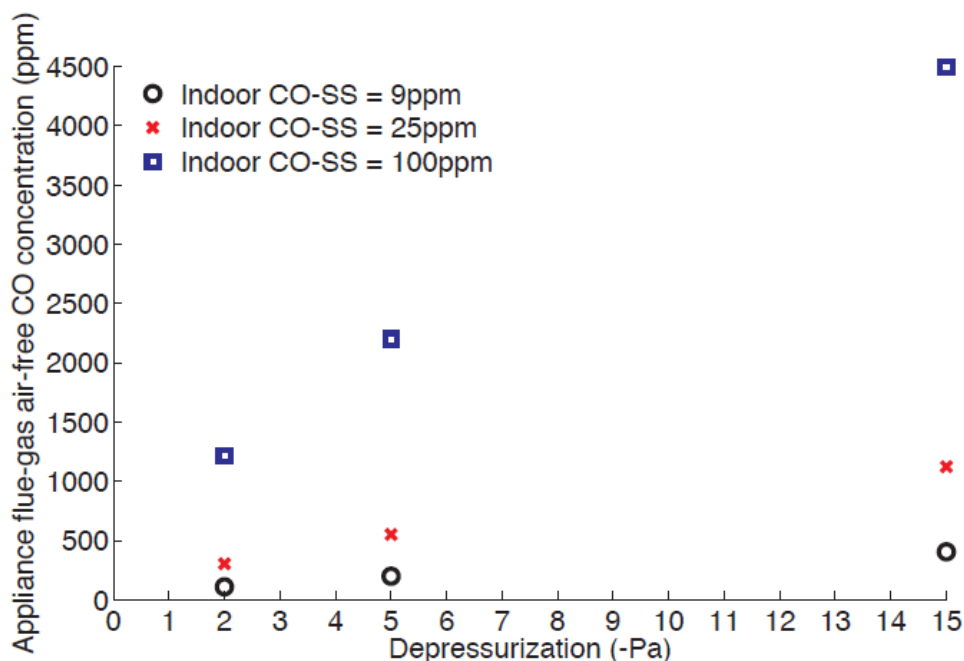
(a) House depressurization = -2 Pa



(b) House depressurization = -5 Pa

Figure C5 shows that reaching a life-threatening indoor CO concentration (100 ppmv) requires very high flue-gas air-free CO concentrations that are rare for an appliance and represent a malfunctioning appliance. For example, at -2 Pa depressurization the required flue-gas concentration is about 1200 ppmv; at -5 Pa depressurization the required flue-gas concentration is about 2200 ppmv; and at -15 Pa depressurization the required flue-gas concentration is about 4500 ppmv. These results indicate that reaching life-threatening conditions in a moderately tight home with a natural draft appliance is rare and almost impossible for an induced draft appliance. However, moderately tight homes may reach an acute health hazard from a single spillage event from a natural draft appliance. In a very tight home (2 ACH₅₀ or tighter), fewer problematic events can lead to a life-safety hazard and these problematic events are more likely occur. The combination of low air exchange rate and increased risk of spillage significantly increases the potential for prolonged pollutant exposure that could lead to a life-safety hazard. Therefore, in very tight homes, we recommend all combustion appliances be direct vent or installed outside the living space.

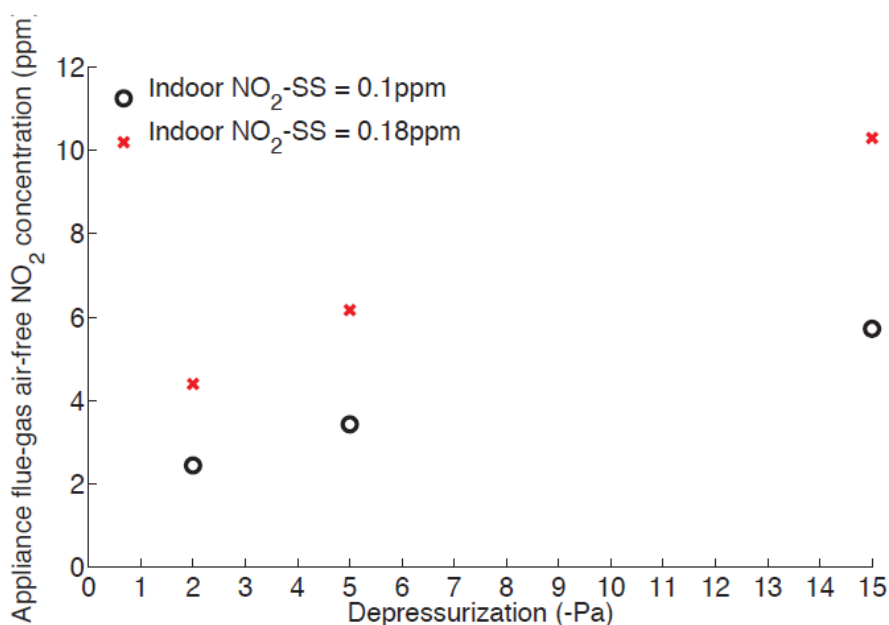
Figure C5: Appliance flue-gas air-free CO concentrations required to reach specified steady-state indoor CO concentrations with varying house depressurization. The house is assumed to be 1200 ft² with an airtightness of $a_{50} = 4 \text{ hr}^{-1}$ containing a 40,000 Btu/h appliance spilling continuously.



Applying the same simulation approach to NO₂, Figure C6 shows the simulated flue-gas air-free NO₂ required to reach steady-state indoor NO₂ concentrations of 0.10 ppmv or 0.18 ppmv at various house depressurizations. A key difference between CO and NO₂ is that NO₂ decays with time, meaning the indoor NO₂ concentration will decrease even in the absence of airflow.

Previous research shows that water heaters emit 3 ppmv of NO₂, and furnaces emit 8 ppmv, on average [32]. The simulated results for NO₂, shown in Figure C6, indicate that a water heater in a moderately tight home emitting 3 ppmv of NO₂ is likely to cause an acute hazard. A furnace, in the same home, emitting 8 ppmv of NO₂ will definitely create an acute hazard, as the indoor concentrations will exceed both the 0.1 ppmv and the 0.18 ppmv thresholds. Even at higher depressurizations (-15 Pa), the results show a furnace still exceeding the 0.1 ppmv threshold, exposing the occupants to acute levels of NO₂. The results from this simulation indicate that in a moderately tight home, spillage from natural draft water heaters and furnaces, as well as induced-draft furnaces, may present an acute NO₂ hazard. Because NO₂ concentrations from the appliance may be difficult to measure, we recommend instead measuring the total oxides of nitrogen (NO_x) and using an upper limit or a fraction of the NO_x that is characteristic to the appliance (e.g., about 10% or less of NO_x exhausted from storage water heaters is NO₂).

Figure C6: Appliance flue-gas NO₂ concentrations required to reach specified steady-state indoor NO₂ concentrations with varying house depressurization. The house is assumed to be 1200 ft² with an airtightness of $a_{50} = 4 \text{ h}^{-1}$ containing a 40,000 Btu/h appliance spilling continuously.



By combining the results presented in Figures C5 and C6, an initial screening tool using flue-gas concentrations measurements could be developed to identify homes with a high and low risk of accumulating indoor CO and NO₂. Although the simulated results should not be used to identify problematic houses near the passing threshold, it could be used as a screening tool to quickly identify very low- and very high-risk homes. Such a tool could help determine how many extensive (and time consuming) combustion tests need to be performed in order to adequately assess the risk. For example, a house that is 3600 ft², with $a_{50} = 8 \text{ h}^{-1}$ (i.e., three times as big as the house simulated in Figure C5 and half as tight), containing a 40,000 Btu/h furnace would need to emit about 13,200 ppmv of air-free CO to reach indoor CO concentrations of 100 ppmv, assuming the furnace spills when the house is depressurized to -5 Pa. The probability that a furnace will emit 13,200 ppmv of air-free CO is extremely low. Therefore, fewer combustion safety tests could be conducted on this house before passing a complete inspection.

C5 THE AIRFLOW DRIVER STUDY

This study characterizes the drivers of airflows in and out of a small house. Compared to the spillage study of Section C4, which treats the house pressure as an independent variable, and the whole-house air change rate as the dependent variable, the airflow driver study takes a more mechanistic view. It adopts a network flow approach, in which airflows result from wind, temperature differences, and mechanical ventilation acting on specific flow paths. In this formulation, the house pressure with respect to outdoors reflects the balance between these driving forces, and the whole-house air change rate is the sum of airflows entering or leaving the house through the individual paths.

Two main observations motivate examining the airflows, and the resulting pressures, in greater detail:

- When a properly-operating vent shaft draws air out of the house, it contributes to depressurizing the house (by increasing the flow of air into the house via adventitious leaks, which induces a pressure drop in the flow direction). As the flow out the vent shaft increases, and the house pressure falls further, the *likelihood* of backdrafting falls.
- Consider the tipping point where an exhaust fan is just strong enough to reverse flow in the vent shaft. Then any additional mechanical exhaust will bring outside air into the house through the vent, tending to dilute the combustion gases. As the exhaust fan flow increases, and the house pressure falls further, the *consequences* of backdrafting decrease.

Thus, the most dangerous conditions probably arise when the vent shaft flow is nearly zero. Starting from zero vent shaft flow, it is possible to improve the indoor air quality either: (1) by forcing air to leave the house through the vent shaft (thus exhausting the combustion gases); or (2) by forcing air to enter the house through the vent shaft (thus diluting them). While relying on dilution obviously does not constitute safe design, it does mean that the worst-case scenario for human health may occur at modest depressurization rather than at maximum depressurization.

These observations make clear that the direction of flow in the vent shaft, rather than depressurization per se, is the measure of interest when testing a house for backdrafting problems. The depressurization limits described in Section C2 attempt to account for this by examining the additional depressurization induced by the exhaust fans, rather than the pressure drop across the building envelope. However, even this change in pressure is an indirect measure of the true value of interest.

To better understand this issue, consider a pressure-based field test to determine the direction of flow in the vent shaft. Since the flow relates to the pressure drop through the vent shaft, evidently measuring Δp_h across the vent shaft can predict the flow direction. However, measuring the house gauge pressure between any other indoor and outdoor locations will shift its value. Furthermore the extent of the shift will depend on all the drivers of airflow, with the temperatures and wind speed being among them. Therefore Δp_h will be an imperfect predictor of the point of zero vent shaft flow. From Equation C1, the same is true of Δp_f .

C5.1 Modeling

To explore these issues, we developed a simple airflow model of a house, using the CONTAM multizone airflow and pollutant transport simulation tool [36].

Multizone models such as CONTAM relate airflows to pressure drops in discrete flow paths. Wind, temperature differences, and mechanical equipment generate pressures that drive flow - akin to voltages driving current in an electrical network. The airflow network solver finds the pressures that balance the mass flow of air entering and leaving each space through all the defined flow paths [20]. Multizone models also include contaminant transport, solving expanded versions of the single-zone mass balance shown in Equation C2. However, since the

airflow driver study focuses on the steady-state airflows, the model used here does not include contaminants.

The “no-combustion” airflow model used here defines a single zone, representing the house interior. Three types of flow paths connect this zone to the outdoors: the exhaust fan, the vent shaft, and adventitious leaks in the building envelope. Adventitious leaks follow a power law relationship similar to Equation C16. The vent shaft uses the Darcy-Colebrook model, a pressure-flow relation specialized for ducts.

To explore how ambient conditions, plus some design parameters, affect backdrafting in a cold vent, we varied key inputs to the no-combustion airflow model, including: the outdoor temperature and wind speed; the exhaust fan flow rate; and the whole-house leakage characteristics. Table C8 gives details for the adjustable parameters. Table C9 lists the fixed model parameters of interest.

Table C8: Adjustable parameters in the CONTAM model used for the airflow driver study.

Parameter	Value
Vent shaft flow resistance	2 or 4 elbows. Each elbow modeled with pressure loss coefficient of 0.34, corresponding to 90-degree elbow with 3 gores and radius/diameter ratio of 1.5 [1].
Blower-door leakage, a_{50}	Total leakage area of adventitious leaks adjusted to make whole-house leakage one of 2, 3, 5, or 10 air changes per hour at 50 Pa.
Vertical distribution of adventitious leaks	For “high” distribution, 2/3 of leakage area at ceiling level, and 1/3 at floor. For “low” distribution, 1/3 at ceiling, 2/3 at floor.
Outdoor temperature, T_{out}	0, 20, or 40°C.
Wind speed, u	0, 2, 4, or 8 m/s.
Forced flow due to mechanical exhaust, Q_f	0, 100, 200, 400, or 600 cfm.

In Table C8, note that the vent shaft resistance and whole-house leakage parameters interact. In particular, the whole-house leakage includes the vent shaft resistance, which varies with the number of elbows assumed. For each vent shaft configuration, we tuned the total leakage as follows: (1) Set natural ventilation to zero, by making both indoor and outdoor temperature the same (20°C), and by setting the wind speed to zero. (2) Set the exhaust fan flow rate to the desired air change rate, a_{50} . (3) Adjust the flow element representing adventitious leaks, in order to make the house pressure 50 Pa.

Of course, this simple model lacks some features. Most importantly, it does not include combustion. Specifically, the model does not include a source term for combustion products. Nor does it include combustion-related heating in the vent shaft, or any airflows related to providing make-up air for combustion. This was due mainly to limitations of the simulation tool: CONTAM does not include coupled thermal-airflow calculations. Note, however, that neglecting combustion-related heating in the vent shaft makes the model conservative in terms

of human health (because the start-up of the combustion appliance, when the vent shaft is least inclined to draft, represents the worst case).

Table C9: Fixed parameters in the CONTAM model used for the airflow driver study.

Parameter	Value
Floor area	1200 ft ² . Represents small California house.
Structure height	Interior height, 8 ft. Roofline height, 13 ft.
Vent shaft cross-section	Round duct, diameter 4 in.
Vent shaft heights and length	Bottom at 5 ft. above floor level (estimate based on observations). Top at 3 ft. above roofline. Length set by top-to-bottom height (i.e., length does not depend on number of elbows).
Vent shaft materials	Galvanized steel, “average” roughness 0.15mm [1].
Vent shaft entrance and exit	Terminal loss coefficient indoors 0.05 (“well-rounded entrance” [1]). Terminal loss coefficient outdoors 0.5 (“sharp entrance” [1]).
Vent shaft temperature	Same as house interior.
Adventitious leaks	Power law model flow exponent $n = 0.65$ [36]. Flow coefficient, C_f , set to give desired whole-house leakage.
Horizontal distribution of adventitious leaks	Distributed evenly between upwind and downwind sides of house.
Wind pressure coefficients	Upwind, 0.6 [26]. Downwind, -0.4 [26]. Vent shaft, -0.6 [13].
Indoor temperature	20°C

A second thermal effect the model ignores is heat transfer from the vent shaft to the attic or outdoors.

Even in the absence of combustion, the temperature of air in the vent shaft may not equal the mean of the indoor and outdoor air temperatures (as the model assumes). A follow-on analysis should couple the temperature of air in the vent shaft to the airflow direction, the heat input due to combustion, and heat losses or gains due to conduction through the vent shaft walls.

Other idealizations that may affect the interpretation of the simulation results include:

- The whole-house leakage does not include leakage through the exhaust fan when the fan is turned off. This effect would be easy to incorporate in CONTAM, but we considered that it would unnecessarily couple the fan and leakage parameters.
- The fan flow rate, Q_f , is a constant. A real fan may have a rated capacity corresponding to Q_f , but its actual flow rate decreases as the fan faces greater flow resistance. Again, CONTAM can model this effect. However, doing so would make it harder to reason about the effect of changing a_{50} .
- Flow resistance in the vent shaft doesn’t change with the flow direction. The model ignores the possibility that, for example, a vent cap or damper will have a different resistance depending on the flow direction.

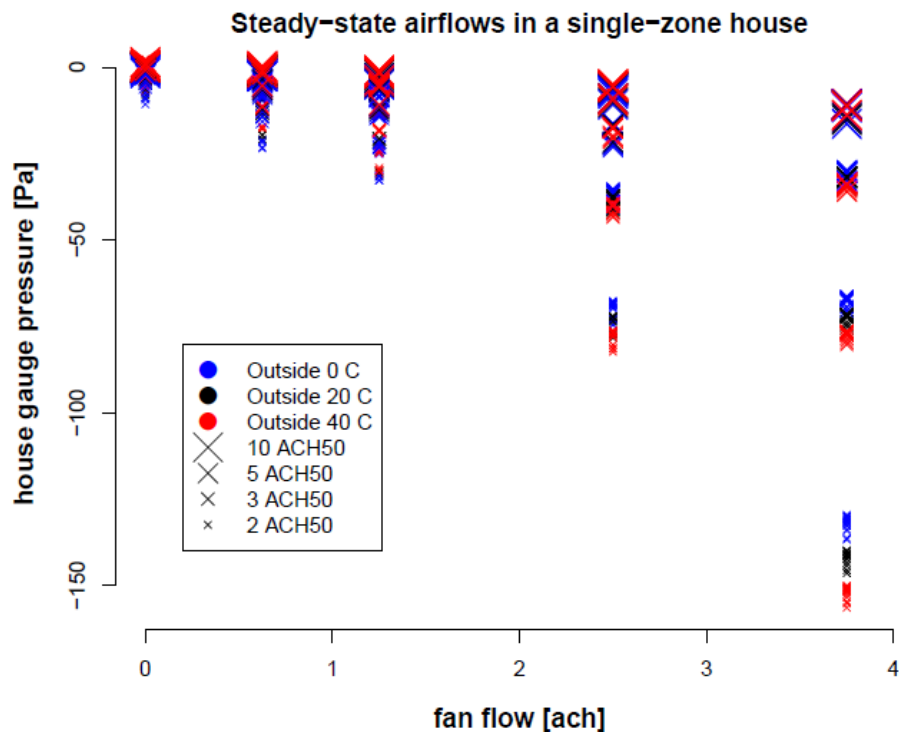
- The model does not include interior partitions. Therefore, it makes no predictions about, for example, the effect of isolating combustion appliances, the effect of opening or closing doors on Δp_f , or the relative safety of different floors within the house.
- For a combustion safety analysis, the vent shaft wind pressure coefficient may be optimistic, as it assumes suction on the vent no matter what the wind direction may be.

C5.2 Results for the Airflow Driver Study

Each run of the model predicted the airflows for a fixed house configuration, with a single set of airflow drivers. From each run, we recorded: (1) the indoor-to-outdoor pressure difference, Δp_i , measured at floor level; (2) the indoor-outdoor air change rate, a ; and (3) the airflow in the vent shaft, with positive values representing flow through a properly-drafting vent, i.e., out of the house.

Figure C7 shows the house gauge pressure as a function of the exhaust fan flow. Fan flow, though specified as a volume flow rate, has been normalized to air changes per hour. The house pressure is measured with respect to outdoors, such that negative values indicate depressurization.

Figure C7: The house interior pressure depends mainly on the mechanical exhaust rate and the leakage class. Other variables - the wind speed, indoor-outdoor temperature difference, and vertical leakage distribution - introduce some variation, but become less important as Q_f increases.



As expected, the house gauge pressure depends strongly on the fan flow rate and the leakage class, with the tightest house depressurizing the most as a result of mechanical exhaust. Nevertheless, for a given fan flow and leakage class, indoor-outdoor temperature differences do

affect the interior pressure. This is most obvious at the highest fan flow and tightest leakage class, where the three clusters of predicted pressures are distinguished by the outdoor temperature (with wind speed introducing most of the variation within each cluster).

At lower fan flows, wind and temperature effects are more important. For example, at zero fan flow, a close-up of Figure C7 would reveal that the tightest house has not only the largest depressurization (most negative Δp_h), but also the largest over-pressurization (most positive Δp_h). In addition to being more strongly influenced by mechanical ventilation than a relatively leaky house, a tight house also has larger weather-related pressure swings.

To examine the zero fan flow case in more detail, Figure C8 plots the predicted house gauge pressure against the flow in the vent shaft, for $Q_f = 0$. Again, positive flow means air leaves the house through the vent shaft. Most of the $Q_f = 0$ simulations predict that air exits the house through the vent shaft. This largely results from the negative wind pressure coefficient at the vent cap, which ensures that wind always exerts suction on the vent shaft. In addition, lower outdoor temperatures also encourage flow out of the house via the vent shaft, as cold outdoor air enters the house near ground level, and warm indoor air exits through the higher flow paths.

Figure C8 also shows that positive vent shaft flows correlate strongly with $\Delta p_h < 0$. As air exits the house through the vent shaft, make-up air enters through adventitious leaks. This vent airflow depressurizes the house with respect to the outside.

For a given house, decreasing the outdoor temperature increases outflow through the vent shaft, and increases the house depressurization. Thus the figure confirms that $\Delta p_h < 0$ does not, by itself, indicate a problem with negative flows in the vent shaft. In fact, *with no mechanical exhaust, only hot, relatively windless days* produce negative flow in the vent shaft (since thermal buoyancy encourages cool indoor air to flow out through the lower leakage paths, turning the vent shaft into a make-up path).

For a given set of ambient conditions in Figure C8, a tighter house means smaller vent shaft flows. Therefore tightening the house has two negative effects in terms of combustion safety: (1) it reduces the natural (buoyancy- and wind-induced) flows out the vent shaft during periods when fans are not operating; and (2) as seen in Figure C7, it makes the house more susceptible to fan-induced depressurization, and hence to backdrafting.

Turning from house pressure to flow direction as the primary indicator of the vent shaft performance, Figure C9 plots the vent shaft flow against the fan flow (Q_f). As before, at $Q_f = 0$ the majority of cases have positive flow out the vent shaft. Increasing the fan flow makes the vent flow more likely to reverse, especially for tight houses. However, for a relatively leaky house with $a_{50} = 10 \text{ h}^{-1}$, positive vent shaft flows are still possible, even at the largest fan flow studied. Of course, since this study does not account for the joint distribution of temperatures and wind speeds at a particular location, a real house would not have the same proportion of positive vent shaft flows as shown in Figure C9.

Figure C8: With no fan running, $\Delta p_h < 0$ means the vent shaft is working as desired. For zero exhaust flow, positive vent shaft flow (out of the house) is the norm. This depressurizes the house relative to outdoors. Only hot, relatively windless days reverse flow in the vent shaft.

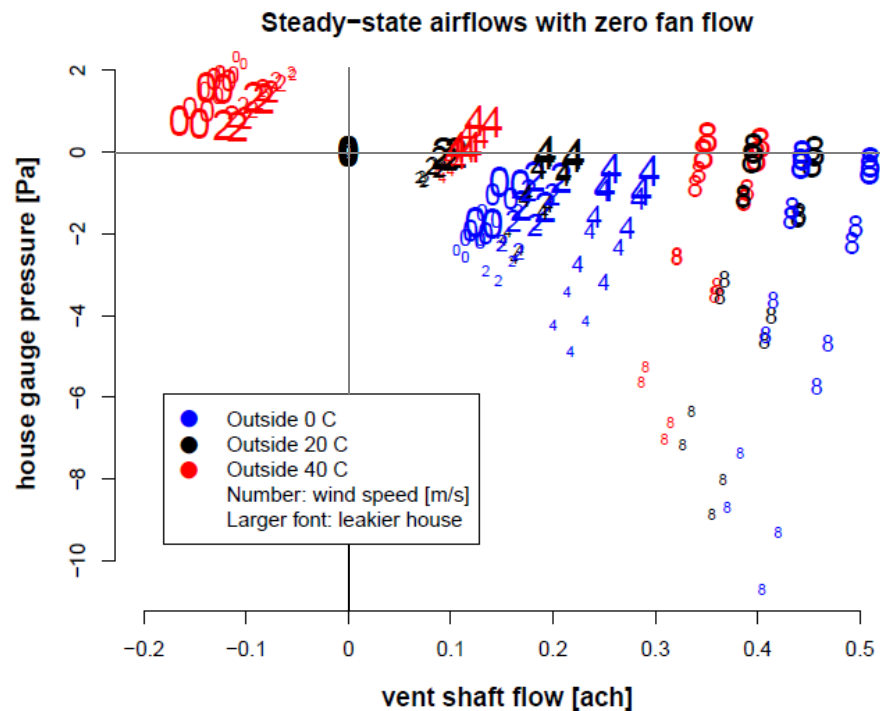


Figure C9: Large exhaust flows do not necessarily reverse the flow in the vent shaft. Tighter houses, hotter outdoors, and lower wind speeds all increase the risk of negative flow.

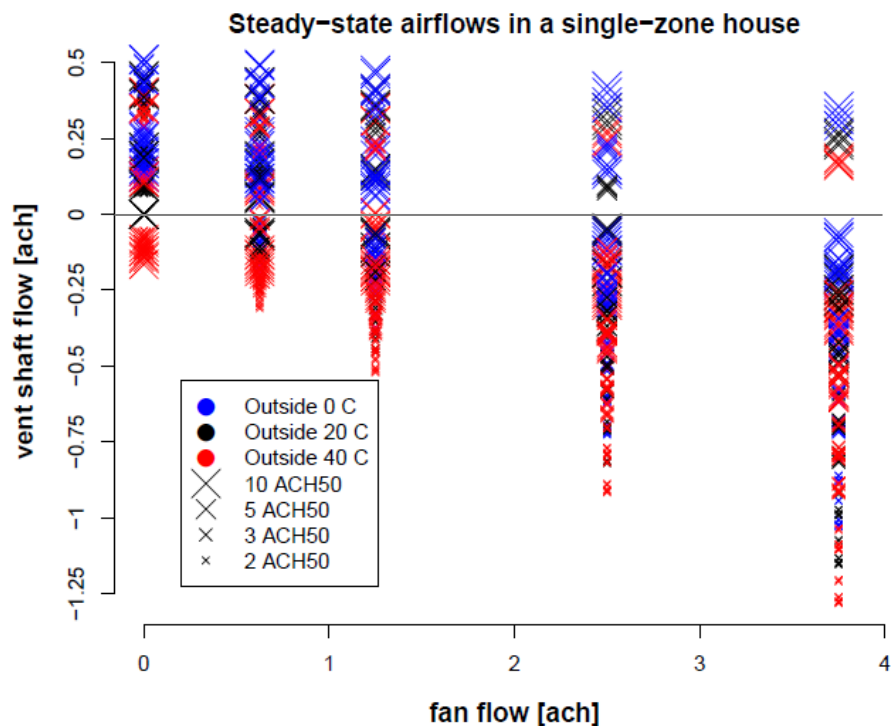
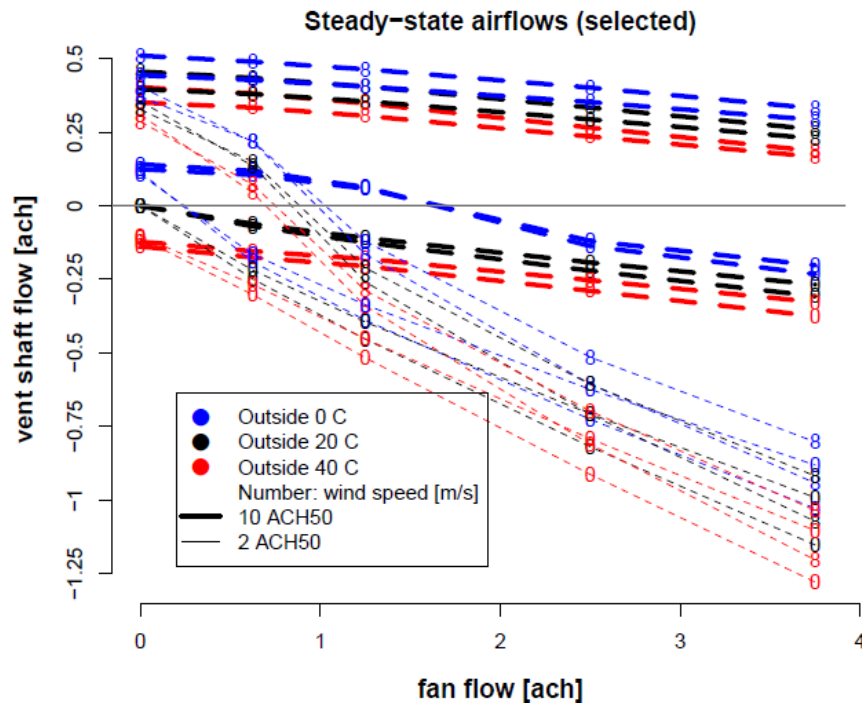


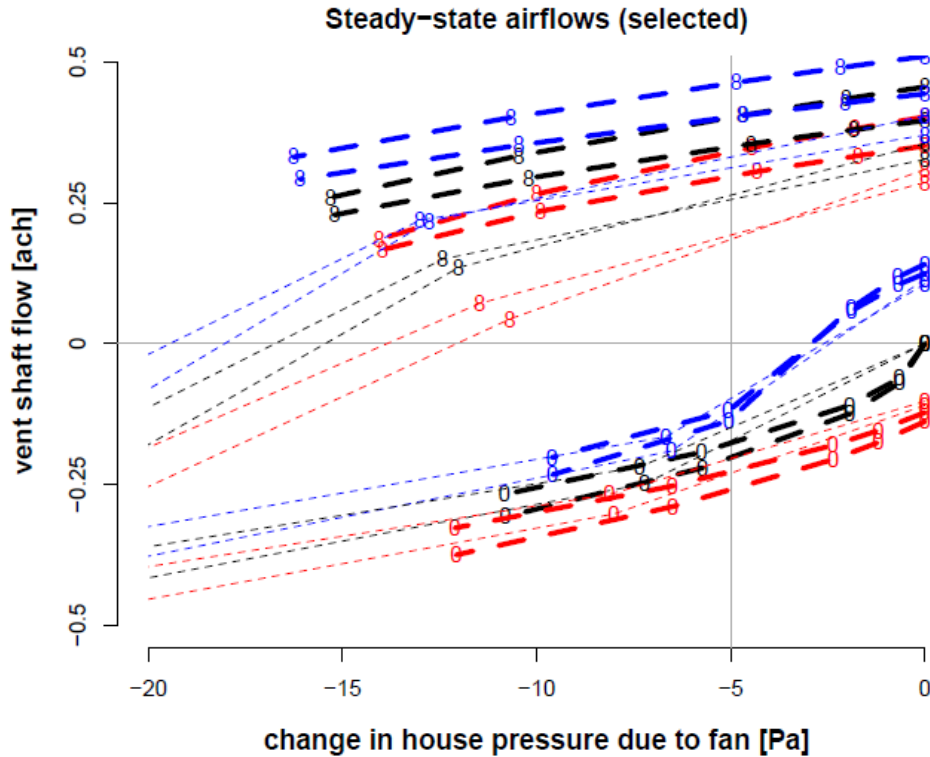
Figure C10 shows a subset of the results from Figure C9. To make the relationships between the model predictions easier to follow, it shows only the tightest and leakiest houses in the study, only the houses with “high” vertical distribution of leaks, and only the highest and lowest wind speeds. This still leaves variations due to the number of elbows in the vent shaft (as suggested by the paired lines for each leakage class, temperature, and wind speed). As seen before, running an exhaust fan makes outside air more likely to enter the house via the vent shaft. Tightening the house makes it easier to reverse the vent shaft flow, while higher wind speeds, and cooler outdoor air, make it harder to reverse flow.

Figure C10: Increasing the exhaust fan flow reduces flow out the vent shaft, but does not necessarily reverse it. Tighter houses, hotter outdoors, and lower wind speeds are more susceptible to backdrafting. For clarity, the plot shows only the tightest and leakiest houses, houses with a “high” vertical distribution of vertical leaks, and the highest and lowest wind speeds.



Turning to the question of field tests, Figure C11 shows the vent shaft flow against the fan-induced pressure change. As with Figure C10, the plot reduces visual clutter by showing only the “high” vertical distribution results, the tightest and leakiest houses in the study, and the highest and lowest wind speeds. At $\Delta p_f = 0$ (i.e., with the exhaust fan off), the vent shaft flow for a given house depends only on wind and outdoor temperature. Thus, the points on the far right of Figure C11 correspond to the “baseline” condition of an induced-depressurization stress test. Increasing the exhaust fan flow makes both Δp_f and Δp_h more negative. Since the vent shaft requires a positive pressure drop from indoors to outdoors in order to draw air out of the house, increasing the exhaust fan flow reduces the vent shaft flow, eventually reversing it (if it was not negative already).

Figure C11: For a particular house and weather conditions, increasing the exhaust fan flow rate makes both the house interior pressure and the vent shaft outflow more negative than before. Consistent with Figure C10, the line thickness shows the leakage class, the number shows the wind speed, and the line color corresponds to outdoor temperature. For clarity, only the tightest and leakiest houses, houses with a “high” vertical distribution of vertical leaks, and the highest and lowest wind speeds are plotted.



Although Figure C11 does not make explicit the number of elbows in the vent shaft, in general for a given value of Δp_f in an otherwise comparable simulation, a vent shaft with two elbows has a larger-magnitude flow than one with four elbows. In part this is due to the way the simulation study defines “comparable” houses: increasing the number of elbows increases the vent shaft’s resistance to flow, and hence makes the adventitious leaks larger, in order to achieve the specified a_{50} . Thus, increasing the elbow count tends to shift all airflows, whether driven by outside conditions or by the exhaust fan, out of the vent shaft, and into the adventitious leakage paths. This explains the crossing of lines in Figure C11 as fan-induced pressure change becomes more negative.

The field tests described in Section C2 assume that Δp_f is a good predictor of the potential for vent shaft flow reversal, with $\Delta p_f = -5$ Pa as a typical limit. As Figure C11 makes clear, the fan-induced pressure change does *not* predict reverse flow, since: (1) hot, calm days start with reverse flow even at $Q_f = 0$; and (2) windy days make flow reversal unlikely, even in a tight house, and even out to $\Delta p_f \approx -10$ Pa.

Of course, to be a good predictor of the potential for reversal, the fan-induced pressure change does not have to predict reversal in every situation. It merely has to predict whether flow can

reverse in the worst cases - for example, on hot, calm days. In this regard, Figure C11 points out several deficiencies of induced-depressurization stress testing:

- Weather conditions at the time of the field test indeed will affect the test results. In Figure C11, the lines represent a particular house operating under particular weather conditions. The numbers along each line, in addition to giving the wind speed, also mark the actual Δp_f predictions. Therefore, following each line from right to left, Q_f jumps from 0, to 100, to 200 cfm, and so on, at each marker. Thus the leakier houses ($a_{50} = 10 \text{ h}^{-1}$) typically reach $\Delta p_f = -5 \text{ Pa}$ between $Q_f = 200$ and 400 cfm . However, comparing curves for the same house configuration shows that the exact fan flow at which each house would fail the induced depressurization stress test depends on the weather conditions at the time of the test. For example, at $T_{out} = 0^\circ\text{C}$ and wind speed (u) = 8 m/s , the leakier houses experience a fan-induced pressure change of -5 Pa at an exhaust fan flow rate of about 200 cfm . At $T_{out} = 40^\circ\text{C}$, the same house requires nearly 400 cfm of exhaust to reach the same depressurization limit.
- A house can experience backdrafting even if it passes the depressurization test. Several of the curves in Figure C11 show the possibility of negative vent shaft flow for exhaust rates that do not push the house beyond the $\Delta p_f = -5 \text{ Pa}$ depressurization limit. For these houses, if the combustion appliance turns on while the fan is running, there is no guarantee that the vent shaft will be able to establish draft in order to achieve a positive flow.

When interpreting Figure C11, it is important to remember that it shows *steady-state* airflows for a house with no combustion appliance operating. Heating the gases in the vent shaft would make the vent more prone to upward flow, and would shift all the curves upward, toward more positive vent shaft flow. Unfortunately, CONTAM does not allow independent control of the air temperature in the vent shaft, so we cannot generate such a plot using the tools at our disposal.

Summarizing, Figure C11 demonstrates that: (1) any depressurization test will be sensitive to the weather at the time of the test; (2) a house that fails a depressurization test will not necessarily show backdrafting, since buoyancy and wind effects may favor upward flow in the vent shaft; and (3) conversely, the vent shaft may have downward flow, even if the house passes a depressurization test.

These observations imply that assessing the potential for dangerous backdrafting depends on the *statistical* correlations of wind and outdoor temperatures for the house in question. The yearly distribution study, which is described in the next section, addresses this question.

C6 THE YEARLY DISTRIBUTION STUDY

This study uses historical weather data to find the airflows, and the resulting CO concentrations, from a simple house model. Driving the model with observed weather conditions accounts both for the relative frequency at which different temperatures and wind speeds occur, and for the correlation between them. Therefore, it gives a more realistic picture of the danger of backdrafting than the airflow driver study (which was intended to identify key

parameters), with its uniform grid of assumed conditions. Furthermore, predicting the time evolution of CO concentrations in the house gives a direct assessment of the resulting threat to occupant health.

C6.1 Modeling

The model for the yearly distribution study closely resembles that for the airflow driver study. However, we modified it slightly, to avoid one particularly unrealistic implication of the well-mixed assumption. Specifically, the box model described in Section C5 has only one zone. Therefore, CONTAM would predict that any pollutants produced by the combustion appliance mix instantly throughout the house. That is, no matter how strongly the vent shaft draws air out of the house, all source emissions would be assumed to enter the occupied space. This effect strongly biases the single-zone model toward predicting high indoor concentrations.

To overcome this bias, we added a small (1 m^3) combustion appliance zone to the model. The vent shaft connects the CAZ to the outdoors, and a power-law orifice model connects the CAZ to the occupied space. With this arrangement, if air leaves the house through the vent shaft, then CONTAM will predict that all emissions in the CAZ exit the house directly, without entering the occupied space. Conversely, for negative flow in the vent shaft, all the source emissions enter the occupied space.

Note that, while we refer to this secondary zone as a combustion appliance zone, we did not attempt to model the physical details of a CAZ. Rather, we added this secondary zone solely as a modeling device, to ensure that positive vent shaft flow prevents combustion products from entering the occupied space. Therefore, we do not report concentration predictions for this secondary zone.

To keep the airflow predictions from this two-zone model as close as possible to those from the single zone model of Section C5, the orifice that connects the CAZ to the occupied zone relatively is permissive to airflow (i.e., a large opening). Specifically, its flow coefficient C_f was set to ten times the sum of the flow coefficients for all adventitious leaks across the envelope. This causes the building shell, rather than the interior partition, to sustain nearly all the pressure drop induced by the exhaust fan. For the resulting two-zone model, the predicted house gauge pressure in the occupied zone, and the vent shaft flow rates, agree with those of the one-zone model to within three decimal digits.

The yearly distribution study also reduces the number of variable parameters in the model. First, it does not distinguish between “high” and “low” vertical distributions of leaks. Instead, it apportions adventitious leaks equally between high and low paths. Second, this study always assumes two elbows in the vent shaft. Both simplifications were based on the observation in the airflow driver study that these model variations did not induce much difference in the airflows.

The weather data consist of hourly observations, recorded over the course of a year, for the 16 California climate zones. Table C10 summarizes the temperatures and wind speeds recorded in each climate zone.

Table C10: Summary of hourly weather data for the California climate zones⁴².

Climate Zone		T_{out} [°C]			u [m/s]	
No.	Name	10 th %	mean	90 th %	mean	90 th %
1	Arcata	5.1	10.7	15.6	2.8	5.7
2	Santa Rosa	6.7	13.7	23.0	2.2	5.1
3	Oakland	9.0	13.9	19.0	4.0	7.2
4	Sunnyvale	8.6	14.1	20.2	4.0	6.9
5	Santa Maria	6.7	13.4	20.6	3.3	6.2
6	Los Angeles	12.2	16.8	21.1	3.4	6.2
7	San Diego	11.0	16.5	22.7	2.5	5.1
8	El Toro	11.0	17.6	25.0	1.9	4.1
9	Pasadena	10.0	17.8	27.0	2.4	4.6
10	Riverside	9.0	17.5	28.0	2.4	5.1
11	Red Bluff	0.0	11.0	21.7	2.4	5.1
12	Sacramento	6.1	15.9	28.0	3.4	6.2
13	Fresno	6.7	17.9	31.1	2.9	5.2
14	China Lake	3.9	18.2	34.0	3.5	7.2
15	El Centro	12.2	24.1	37.0	3.2	6.7
16	Mount Shasta	5.6	16.8	30.6	3.6	7.2

Using these weather data to find the airflows, we drove a dynamic model of the pollutant concentrations over the course of an entire year. Rather than an analytic solution, we let CONTAM solve the governing differential equations numerically. To ensure accuracy, we used the backward differentiation formula (BDF) solver, with relative and absolute convergence tolerances of 10^{-6} and 10^{-10} , respectively [21].

The simulations used a constant indoor source rate $s = 1$ g/h of CO. Since the model includes no outdoor sources and no deposition, the resulting concentration predictions can be scaled to any desired source rate, as suggested by Equation C8. The results presented below scale the source to $s = 5$ and 10 g/h.

The lower source rate, 5 g/h, corresponds roughly to a 35 to 40 kBtu/h appliance generating 400 ppmv air-free CO in the flue (just at the ANSI Z21.10.1 limit [2]).

Two aspects of the resulting model imply that it predicts worst-case exposures:

- The CO source is assumed to be constant, rather than intermittent. Allowing the source to shut off periodically, as was done in the spillage study of Section C4, would lower the long-term average concentration, not only by injecting less pollutant mass into the

⁴² Weather data are available at:

http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=4_north_and_central_america_wmo_region_4/country=2_california_climate_zones/cname=California%20Climate%20Zones.

house, but also by occasionally turning the source off during the most challenging weather conditions. We used a constant source specifically in order to predict worst-case concentrations, and to avoid the uncertainties associated with scheduling the source.

- The airflow model ignores heating in the vent shaft, and so under-estimates flows out the vent shaft. As described in Section C5, this modeling defect cannot be avoided when using CONTAM.

On the other hand, one aspect of the model makes it consistently reduce the predicted indoor concentration of CO, compared to reality. The outdoor concentration of CO is assumed zero. To accommodate nonzero background concentrations, the model predictions could all be increased by the outdoor concentration C_o , as shown in Equation C11.

The assumption that the exhaust fan runs continuously cannot be described as always producing worst-case or best-case exposures. As noted earlier, while an exhaust fan can reverse flow in the vent shaft, it also can dilute the contaminant source, and thus reduce indoor exposure. To bracket this effect, we modeled several levels of exhaust, just as in Section 5.

One model implementation detail is particularly important for this study. We calculated the whole-house air change rates directly from the airflows, rather than using CONTAM's estimate. CONTAM Version 3.1 assumes a fixed air density when converting airflows to a whole-building air change rate. While this does not affect the accuracy of the airflow calculations, it does mean that the reported air change rate does not account for pressure-related changes in density. Since the weather files include atmospheric pressure, we calculated the air change rate outside of CONTAM, taking density into account.

C6.2 Results for the Yearly Distribution Study

Each model run predicted hourly airflows and pollutant concentrations for a particular house, in a particular climate zone, and with a fixed exhaust fan flow rate. To show the incidence of backdrafting, Figure C12 plots the cumulative distribution of vent shaft flow, with each curve representing a single run of the model.

The top subplot of Figure C12 shows a tight house, with $a_{50} = 2 \text{ h}^{-1}$. With no exhaust, the houses tend to have positive vent shaft flow (i.e., out of the house) in all climate zones. Since the model does not include heating in the vent shaft, this is largely due to wind-induced suction. As detailed in the airflow driver study, only hot, calm days give negative vent shaft flows. Figure C12 shows that such conditions occur, at worst, less than 20% of the time for the weather files used in this study. As expected, turning on an exhaust fan makes the vent shaft flows more negative. For the tightest houses, even the smallest exhaust fan modeled, $Q_f = 100 \text{ cfm}$, can induce negative vent shaft flow most of the time.

In contrast, the lower subplot of Figure C12 shows the cumulative distribution of vent shaft flows for a relatively leaky house ($a_{50} = 10 \text{ h}^{-1}$). Because the adventitious leaks offer less resistance to flow than in the tighter house, the vent shaft provides less of the makeup air for the exhaust fan. This lowers both the frequency and the magnitude of negative vent shaft flows.

Figure C12: The vent shaft flow rate depends more strongly on the exhaust fan flow rate than on the weather. Nevertheless, at low exhaust rates, the climate zone does have a significant effect on the incidence of positive vent shaft flow. A leakier house makes it harder for an exhaust fan to reverse flow in the vent shaft.

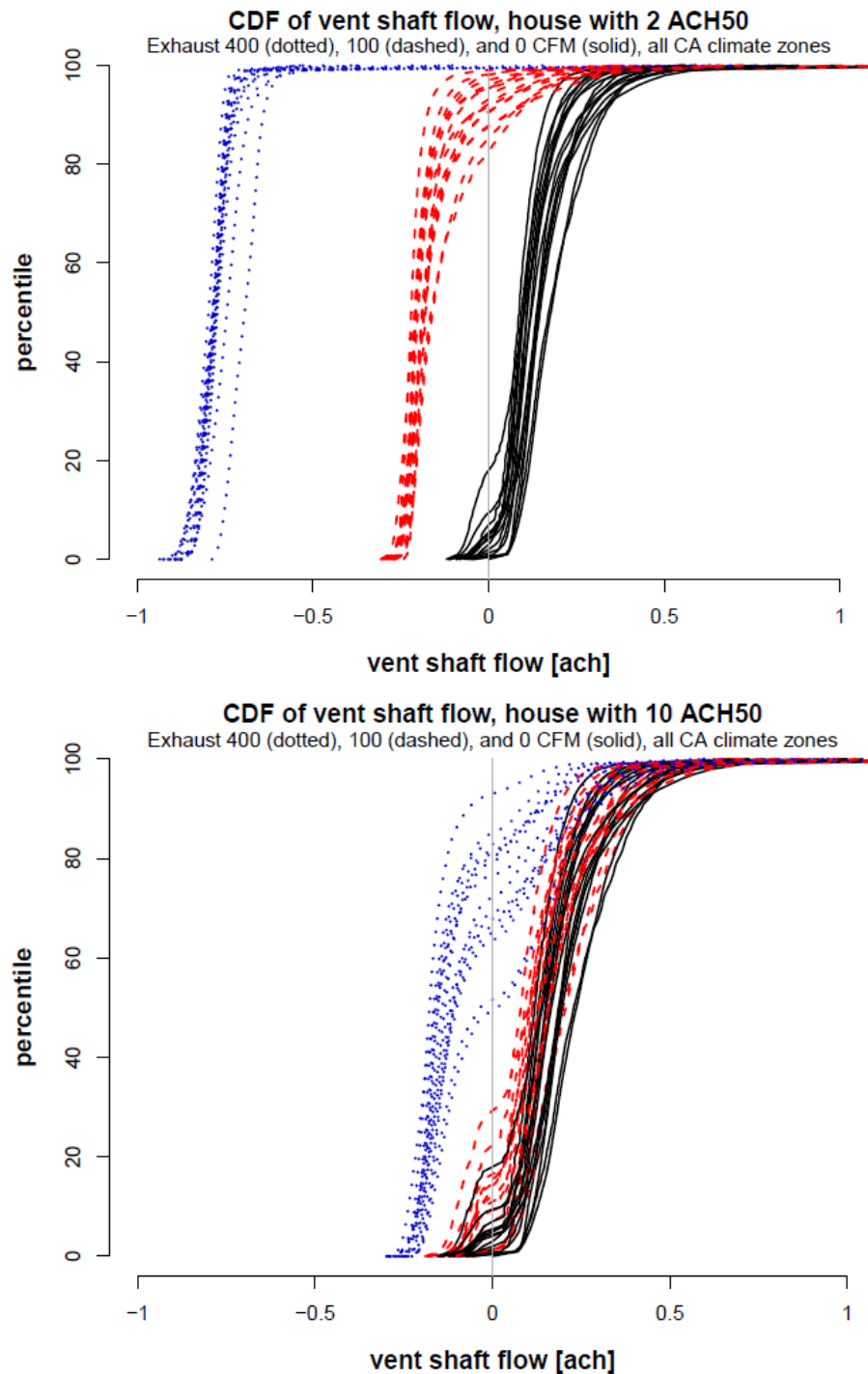


Figure C12 shows the frequency with which negative *flows* occur, but *not* the indoor air quality consequences. To examine those consequences directly, Table C11 summarizes the fraction of time that the predicted indoor CO concentrations over the course of a year exceed the CPSC

one-hour limit of 25 ppmv (Table C4 lists this and other regulatory limits) for each house configuration and climate zone.

For example, the top row of Table C11 summarizes results for a house with an airtightness of $a_{50} = 2 \text{ h}^{-1}$, situated in the Arcata climate zone. For this house, the model predicts no exposure problems when the exhaust fan is off, no matter what the generation rate. From Table C10, Arcata is relatively cool, encouraging consistent outflow through the vent shaft.

Nevertheless, running the exhaust fan at $Q_f = 100 \text{ cfm}$ makes the house exceed the CPSC limit 78% of the time at $s = 5 \text{ g/h}$, and 94% of the time at 10 g/h . The latter statistic implies that exhausting air at 100 cfm for this house and climate zone causes backdrafting such that indoor concentrations exceed 25 ppmv at least 94% of the time. At the lower generation rate, simply reversing flow in the vent shaft is not sufficient to raise CO concentrations above the CPSC limit.

Continuing across the top row of Table C11, exhausting air at 200 cfm increases the frequency and strength of backdrafting. For the lower source rate, this increases dilution enough to reduce the indoor concentrations below the CPSC limit throughout the entire year. For the higher source rate, though, the higher frequency of backdrafting increases indoor air quality problems. With 400 cfm of exhaust, dilution once again overwhelms even the higher source rate.

Finally, moving down the table shows that making a house in the Arcata climate zone leakier reduces the predicted frequency of air quality problems for a given exhaust fan flow rate and CO generation rate. Leakier houses make it harder for the exhaust fan to induce backdrafting.

These observations, taken from a single climate zone in Table C11, echo themes already noted in the previous studies: namely, that tightening the house does increase the risk of fan-induced backdrafting, but that the worst case may result from relatively *modest* exhaust flows. In addition, they emphasize the fact that the blame for indoor air quality problems must, in the end, be assigned to the combustion appliance itself. With the conservative airflow model used here, some backdrafting is inevitable, and the constant generation schedule means that backdrafting always transports combustion products to the occupied space. Therefore, an appliance with a sufficiently high CO generation rate can always cause unacceptable concentrations in the occupied space. Ultimately, tightening a house increases risk because it lowers the generation rate at which significant problems may appear.

To explore the interactions between these variables further, the following discussion focuses on three climate zones:

- Oakland (Zone 3) is among the climate zones predicted to have the fewest problems. In the tightest house, concentrations exceed the CPSC limit only 54% of the time, for 100 cfm of exhaust and the lower generation rate.
- El Toro (Zone 8) is predicted to have the highest incidence of unacceptable indoor air quality for the exhaust fan at 100 cfm. This holds for the tightest leakage classes, and both source rates. This implies that, among all climate zones, the lowest exhaust fan flow most consistently forces the vent shaft flow nearly to zero in El Toro.

Table C11: Percentage of time over a year that a house with a *continuous* CO source rate s has indoor CO concentrations exceeding the CPSC one-hour limit of 25 ppmv for exhaust fan ratings, Q_f , of 0, 100, 200, and 400 cfm. Percentages are rounded up, so a zero entry means no hour of the year was predicted to have a concentration higher than the CPSC one-hour limit.

Climate Zone		Leakage a_{50} [h ⁻¹]	$s = 5$ g/h Q_f [cfm]				$s = 10$ g/h Q_f [cfm]			
No.	Name		0	100	200	400	0	100	200	400
1	Arcata	2	0	78	0	0	0	94	99	0
		3	0	42	0	0	0	75	88	0
		5	0	3	0	0	0	22	58	0
		10	0	1	0	0	0	1	6	0
2	Santa Rosa	2	3	90	0	0	5	98	99	0
		3	2	57	0	0	4	83	95	0
		5	1	11	0	0	3	46	70	0
		10	1	1	0	0	2	4	15	0
3	Oakland	2	1	54	0	0	1	85	92	0
		3	1	18	0	0	1	52	70	0
		5	1	2	0	0	1	15	30	0
		10	1	0	0	0	1	1	3	0
4	Sunnyvale	2	1	60	0	0	1	86	94	0
		3	1	18	0	0	1	50	76	0
		5	1	1	0	0	1	13	31	0
		10	1	0	0	0	1	1	3	0
5	Santa Maria	2	1	78	0	0	1	92	100	0
		3	1	41	0	0	1	69	88	0
		5	1	5	0	0	1	20	57	0
		10	1	0	0	0	1	1	7	0
6	Los Angeles	2	1	79	0	0	1	95	100	0
		3	1	34	0	0	1	68	92	0
		5	1	4	0	0	1	28	51	0
		10	1	1	0	0	1	5	7	0
7	San Diego	2	4	94	0	0	7	99	100	0
		3	3	57	0	0	6	83	98	0
		5	3	14	0	0	4	46	71	0
		10	2	1	0	0	3	8	19	0
8	El Toro	2	17	98	0	0	25	100	100	0
		3	14	79	0	0	21	95	99	0
		5	11	25	0	0	16	66	87	0
		10	7	4	0	0	12	22	31	0

Table C11, continued.

Climate Zone		Leakage a_{50} [h ⁻¹]	$s = 5$ g/h Q_f [cfm]				$s = 10$ g/h Q_f [cfm]			
No.	Name		0	100	200	400	0	100	200	400
9	Pasadena	2	11	96	0	0	18	99	100	0
		3	9	68	0	0	14	88	98	0
		5	7	20	0	0	11	52	80	0
		10	5	3	0	0	8	13	25	0
10	Riverside	2	8	92	0	0	15	96	100	0
		3	7	67	0	0	12	85	95	0
		5	5	27	0	0	10	57	77	0
		10	4	3	0	0	7	14	32	0
11	Red Bluff	2	10	94	0	0	12	97	100	0
		3	8	76	0	0	10	84	97	0
		5	7	33	0	0	9	46	81	0
		10	5	8	0	0	7	15	33	0
12	Sacramento	2	8	72	0	0	14	92	92	0
		3	7	35	0	0	11	65	82	0
		5	5	6	0	0	9	26	45	0
		10	3	1	0	0	6	8	9	0
13	Fresno	2	12	90	0	0	18	97	100	0
		3	9	57	0	0	15	82	96	0
		5	7	11	0	0	12	38	70	0
		10	4	1	0	0	8	10	14	0
14	China Lake	2	19	82	0	0	26	89	98	0
		3	15	56	0	0	22	72	88	0
		5	12	20	0	0	18	38	65	0
		10	8	6	0	0	13	16	23	0
15	El Centro	2	36	81	0	0	46	94	100	0
		3	30	52	0	0	40	79	89	0
		5	23	18	0	0	33	51	65	0
		10	15	6	0	0	25	27	25	0
16	Mount Shasta	2	12	78	0	0	20	89	97	0
		3	8	40	0	0	16	67	86	0
		5	6	6	0	0	12	29	54	0
		10	3	1	0	0	8	10	10	0

- El Centro (Zone 15) has the highest frequency of unacceptable indoor concentrations when the exhaust fan is off. This holds for all leakage classes, and both source rates. This implies that El Centro has the least favorable natural wind and outdoor temperatures.

Note that the particular selection of climate zones is somewhat arbitrary. As will be seen, at 100 cfm of exhaust and 5 g/h generation, indoor concentrations for the assumed house size tend to cluster very near the 25 ppmv limit, regardless of climate zone. Therefore small changes in the concentration limit used to populate Table C11 can have large relative impacts on the tabulated frequencies.

Because the air quality statistics in Table C11 depend on the concentration limit used to generate the table, Figure C13 shows the predicted concentration histories in the three selected climate zones. This figure compares tight and leaky houses ($a_{50} = 2$ and 10 h^{-1} , respectively), with results for zero exhaust, and for $Q_f = 100 \text{ cfm}$.

In Oakland (in the top row of Figure C13), moderate temperatures and strong winds create positive vent shaft flow throughout the year, provided the fan is off. Therefore, the concentrations generally remain at zero, with occasional hot, calm weather permitting excursions to higher values. Turning the exhaust fan on reverses flow in the vent shaft of the tightest house for most of the year. Therefore, it increases the concentrations in the occupied space, as shown in Figure C13. Because the leakier house (in the right column of the top row) makes negative vent shaft flows far less likely, the normal concentration for the $Q_f = 100 \text{ cfm}$ case again falls back to zero.

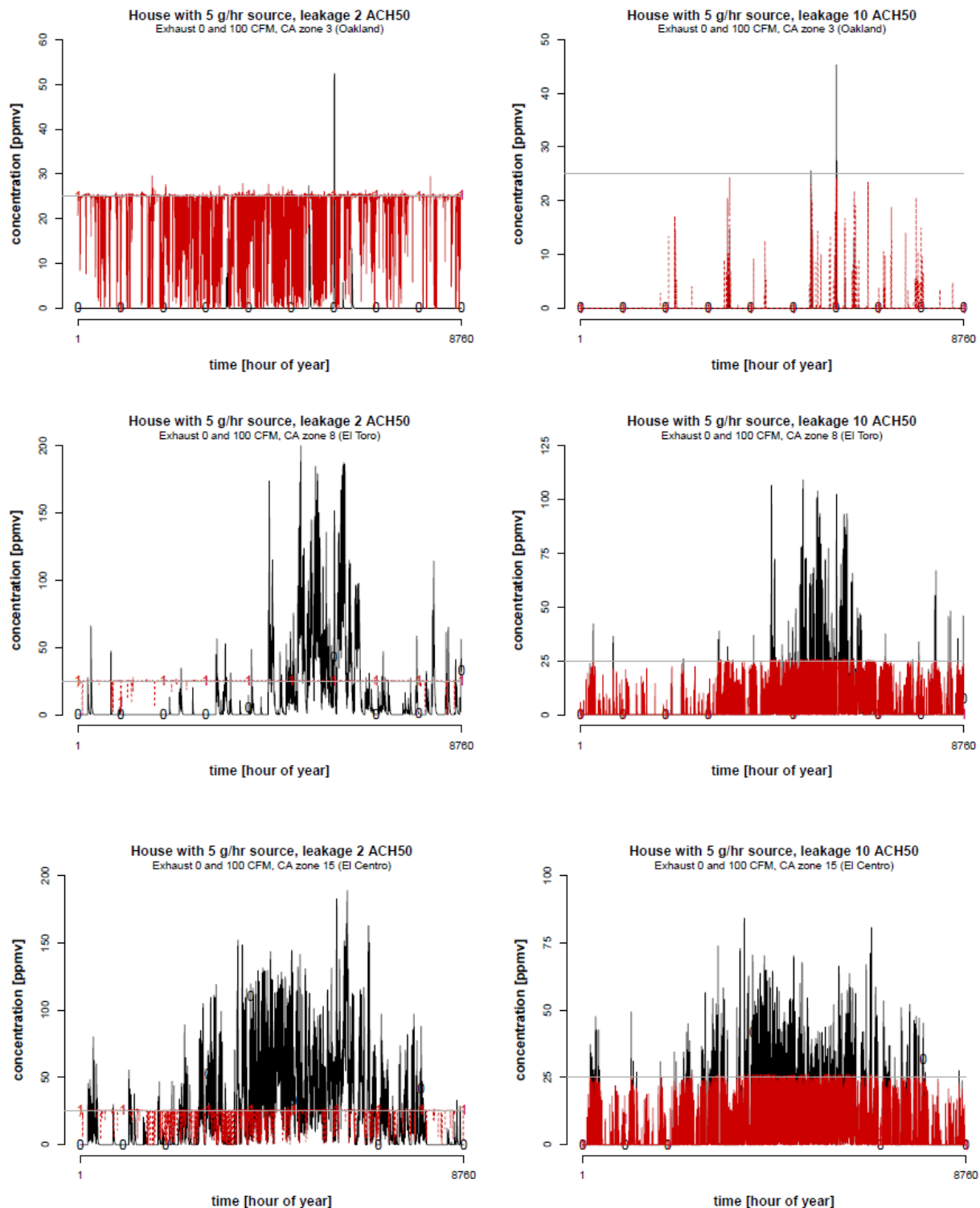
The other two climate zones depicted in Figure C13 show broadly similar patterns. When the fan is off, the vent shaft mostly maintains positive flow, yielding sustained periods of zero indoor concentration, especially in the leakier houses. Periods of hot, calm weather permit negative vent shaft flow, and increased indoor concentrations. Of course, the other two climate zones were chosen because they show much more frequent excursions above the 25 ppmv limit than Oakland. This is particularly noticeable when the fan is off, since peak concentrations correspond to no mechanical ventilation.

When the exhaust fan is on, Figure C13 shows that the concentrations rarely exceed about 25 ppmv, regardless of the leakage class and climate zone. Applying the box model of Section C3 to the occupied zone explains this concentration ceiling. According to Equation C8, the concentration in the occupied zone rises or falls toward some steady-state value σ/λ . For this simple model, the loss rate λ equals the air change rate. When the exhaust fan is on, it establishes the minimum air change rate for the occupied zone: wind and temperature differences can only increase a above that imposed by the fan, and therefore can only reduce the steady-state concentration.

For negative vent shaft flow, the excitation rate σ for the occupied zone depends on the concentration in the combustion appliance zone (which plays the same role as the outdoor concentration C_o in Equation C4).

Because the CAZ is much smaller than the occupied zone, typically it has a higher air change rate, and hence approaches its steady state faster, than the occupied zone. Of course, this is not always true, since the air change rate for the CAZ differs from that for the rest of the house. However, to a first approximation, the concentration in the CAZ may be considered as fixed at its steady-state value.

Figure C13: Concentration over the course of a year, for a tight house (left column) and a relatively leaky house (right column) in three selected climate zones. The black lines are for 0 cfm (no exhaust); the red lines are for 100 cfm exhaust. The horizontal line at 25 ppmv marks the CPSC one-hour limit for exposure to CO. Note that the scale of the concentration axis differs among the subplots.



Again applying the box model (see Equation C7), but now to the CAZ, gives its steady-state concentration as $\sigma/\lambda = s/(aV)$. Here, the product aV is that of the CAZ. For negative vent shaft flow, the mass transport rate into the occupied zone is this same aV times the concentration in the CAZ. Hence, assuming the CAZ is effectively always at steady-state due to its small volume, CO enters the occupied zone at exactly the generation rate s . In short, for a backdrafting vent, typically the distinction between the CAZ and the occupied zone may be ignored, and the occupied zone treated as having a fixed internal source s .

Thus, the concentration ceiling seen for the $Q_f = 100$ cfm cases in Figure C13 corresponds to the fan-limited steady-state concentration, that is, to the steady-state concentration:

$$C = \frac{s}{aV} \quad (26)$$

in the occupied zone when its air change rate, a , is set by the exhaust fan. Doubling the exhaust fan flow rate would halve that upper bound. Of course, doubling the fan flow also could increase the frequency of negative vent shaft flow, causing more hourly concentration predictions to reach the upper concentration bound.

For the houses in Figure C13, $aV = 100$ cfm = 6000 ft³/h, so $s = 5$ g/h yields a steady-state concentration $C = 0.02943$ g/m³. Converting this concentration to regulatory units using Equation 24 requires an assumed temperature and pressure. The indoor temperature in this study was fixed at 20°C, but the barometric pressure was taken from hourly data in the weather files. Using a reference barometric pressure of 101,325 Pa gives $C = 25.27$ ppmv - just slightly above the CPSC limit.

Note that the fan-limited steady-state concentration does not depend on the leakage class of the house. This reflects the assumption that the exhaust fan always delivers its nominal capacity. If we had modeled the pressure-flow characteristics of the fan, such that tightening the house reduced the flow through the fan, then the fan-limited steady-state concentration would rise for a tighter house.

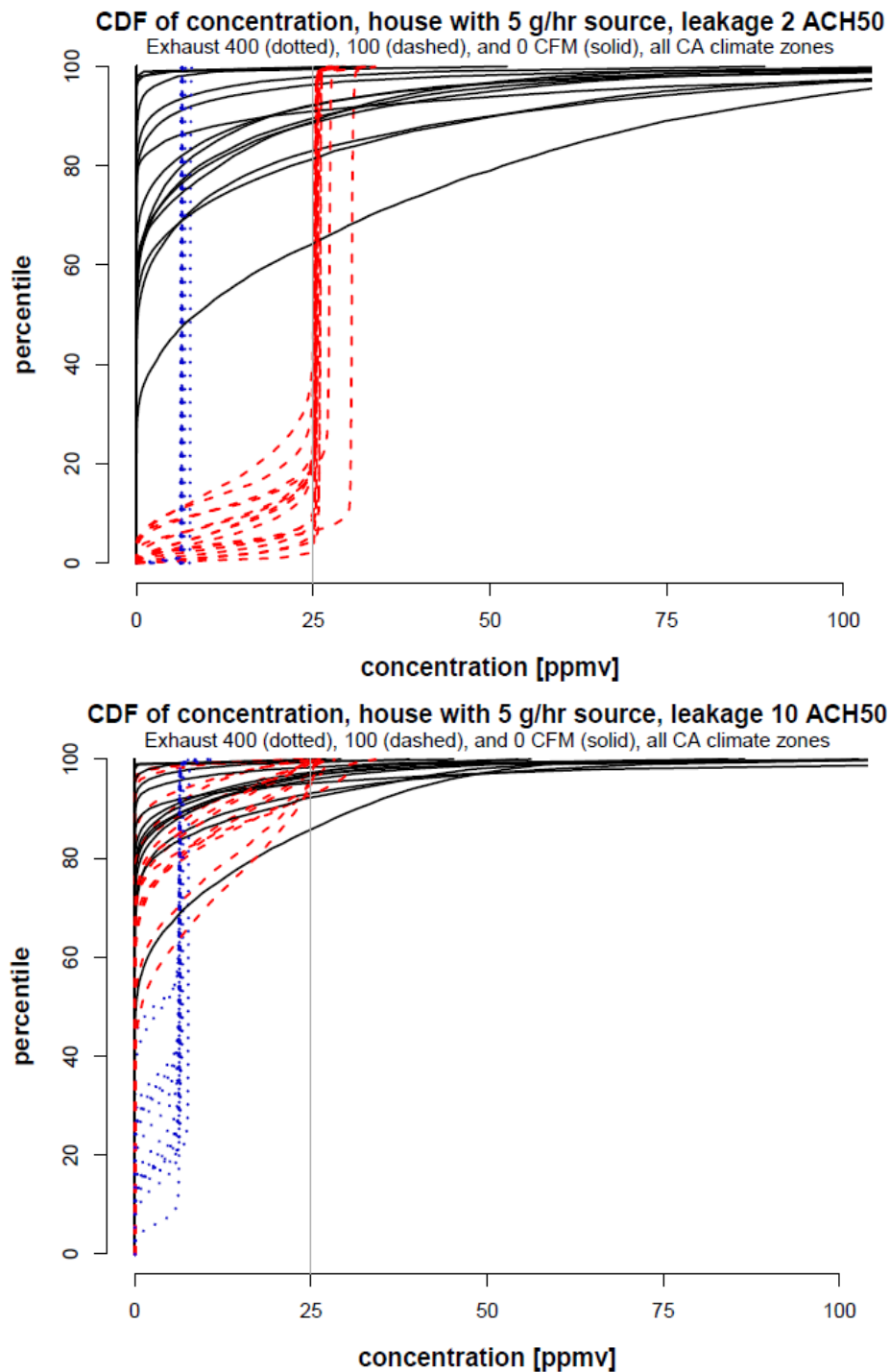
The tendency of the system to evolve toward a steady-state concentration explains the pattern, seen in Figure C13, of a typical “baseline” concentration, with weather-induced excursions. If the exhaust fan is strong enough to reverse the vent shaft flow most of the time, then the apparent baseline is the steady-state concentration of the occupied space with a source $s = 5$ g/h. Weather effects can pull the concentration down from this baseline, either by creating positive flow in the vent shaft (thus cutting off the source), or by making the house air change rate higher than the fan-induced flow rate (thus diluting the source). If, on the other hand, the vent shaft mainly has positive flow, then effectively $s = 0$, and the apparent baseline is a steady-state concentration of zero.

Figure C14 summarizes the concentration results across all climate zones, by showing the cumulative distribution function for predicted concentrations. This figure shows the tightest and leakiest houses modeled, and a source rate $s = 5$ g/h.

Each curve in Figure C14 has a nearly-vertical span of points, representing a large number of predictions at a nearly-constant concentration. As described above, when the exhaust fan is off,

this occurs at $C = 0$, and when the exhaust fan is on, it marks the fan-limited steady-state concentration.

Figure C14: Concentrations in the occupied space depend strongly on the exhaust fan flow rate. With no mechanical exhaust, indoor concentrations vary widely (though there is a bias to zero concentration). Turning the exhaust fan on typically holds the concentration to the fan-limited steady-state.



The cumulative distribution plots make it clear that concentrations fall below the fan-limited steady state concentration far more often than they rise above it. Lower concentrations can result when the air change rate of the occupied zone exceeds Q_f , due to weather. This is a fairly common occurrence, at least at moderate exhaust rates. At higher exhaust fan flow rates, wind and temperature effects are less able to increase the air change rate in the occupied zone. Thus, setting Q_f to 400 cfm not only lowers the fan-limited steady state, it also reduces the volatility of airflow in the occupied zone, and hence widens the band of concentrations at the fan-limited steady state.

The zone concentration also can fall below the fan-limited steady-state due to concentration dynamics. For example, when the vent shaft transitions from positive to negative flow, it may take some time for the occupied zone to fill back to its steady-state concentration.

In principle, the indoor concentration may be able to exceed the fan-limited steady-state, at least for brief periods of time. Suppose the vent shaft flow passes slowly from positive to negative flow. At zero vent shaft flow, the CAZ is isolated, and its concentration can rise without limit. Then, as the vent shaft shifts to negative flow, the CAZ can temporarily supply air to the occupied zone at concentrations in excess of its steady-state value. However, the cumulative distributions shown in Figure C14 suggest that such occasions are rare, if they happen at all. As explained below, the high concentrations observed at the top of each curve are related to pressure effects, rather than to concentration dynamics.

The curves in Figure C14 also make it clear that, even when the exhaust fan causes backdrafting, it can still provide a net benefit in terms of the overall exposure in a house. Because the exhaust fan effectively limits the indoor concentration, it can dramatically reduce the peak concentration in the occupied zone, compared to the no-exhaust case. However, we do not condone this as a design strategy, for two reasons. First, the design goal should always be to avoid backdrafting. Fan-induced dilution, while protective of human health, does not represent a safe approach to indoor air quality. Second, the concentration predictions have to be interpreted in the context of a model that, because it neglects combustion-associated heating in the vent shaft, predicts backdrafting more often than would occur in reality. Thus the high peak concentrations shown for the no-exhaust cases in Figures C13 and C14 almost certainly over-estimate the concentrations that would be observed in a real house.

Finally, we note several aspects of the curves that *apparently* contradict Equation C26. According to that equation, the fan limits the steady-state concentration in the occupied zone to a constant value, which depends only on the source rate s and the volume flow rate aV of flow through the occupied zone. Both are fixed by the model, and therefore the fan-limited steady-state concentration should be fixed as well.

Nevertheless, the concentration ceilings do not always align. For example, at $Q_f = 100$ cfm two climate zones have concentration ceilings considerably higher than the other zones, around 25 ppmv. Furthermore, for each curve, the concentration ceiling has as a slight incline, rather than being perfectly vertical. Finally, for a given curve, the highest concentrations often exceed the concentration ceiling observed for the rest of the curve, and by a significant amount.

These aspects of the figure do not contradict Equation C26, because the equation expresses concentration in volumetric units, for example, $[g/m^3]$, while the figure uses [ppmv]. Despite the name, “parts per million by volume” is not a volumetric concentration. Rather, it gives the mole fraction of contaminant in the total air mixture. Thus it is closer to a mass fraction (the native units of CONTAM) than to a volumetric concentration. For trace concentrations of a particular pollutant, converting between mass and mole fractions requires a constant factor. By contrast, converting to volumetric concentration requires an assumed temperature and pressure, as seen in Equation C24.

In fact, the reason two climate zones have noticeably higher mole fractions at their fan-limited steady-state is that those climate zones have consistently lower atmospheric pressures. The lower pressure means that the house holds a smaller mass of air. This leads to higher mass fractions in the occupied zone, since the source emits CO at a fixed mass rate. A higher mass fraction means a higher mole fraction, giving the results shown in Figure C14. Atmospheric pressure also explains why the curves do not have perfectly vertical bands where the zone reaches its fan-limited steady-state concentration. Expressed in [ppmv], the fan-limited steady-state concentration is not a constant, but varies with temperature and pressure. Finally, note that, had we specified constant mass flow rates for the exhaust fans, rather than constant volume flows, the fan-limited steady-state would show yet a different dependence on pressure in the zone.

C7 CONCLUSIONS AND RECOMMENDATIONS

As described in Section C2, a short-term “stress” test can provide a snapshot of *pressure changes* in a house when one or more exhaust fans operate in the house. However, the simulation studies described in this report raise a number of questions about the suitability of existing stress tests, and the guidelines for their interpretation. Of particular concern is that the tests are fundamentally flawed and are not nearly as useful as people think for the purpose of finding problem situations. For example, in some cases, they are needlessly conservative, potentially leading to unnecessary interventions in houses that do not pose a health risk to their occupants. In other cases, they are not conservative enough, such as their neglecting other harmful combustion pollutants such as nitrogen oxides.

Broadly speaking, the simulations reported here suggest that current limits on fan-induced pressure change, such as those listed in Tables C1 and C2, should be considered only rules of thumb that probably lead to overly cautious air tightening and remediation, and do not necessarily represent worst cases that occur at modest rather than maximum depressurization. Maximum depressurization increases ventilation and reduces concentrations. Consider, for example, the -5 Pa depressurization limit for a furnace and water heater sharing a vent. Simulations show that a house may exceed or fall short of this limit, depending on its air tightness, the exhaust fan size, the weather at the time of the test, and other variables such as the resistance of the vent shaft to flow relative to that of adventitious leaks in the house envelope. Note that these simulations probably over-estimate the risk of spillage. In practice, the -5 Pa depressurization limit derives from field observations, so we believe that accounting for the thermal dynamics would show that the supermajority of houses are safe at that limit. Therefore,

the blind application of that limit, without accounting for factors such as the weather at the time of the test, and the historical distribution of annual wind and outdoor temperature at the site, probably over-estimates the possibility of backdrafting. Therefore, the limit probably causes unnecessary remediation, and possibly discourages energy contractors from tightening houses as much as could be achieved.

Rather than focusing on depressurization, the more important metric involves the indoor concentrations that result from combustion gas spillage. Broadly there are three levels of hazard that can result:

1. Life-safety hazard when CO reaches concentrations above 100 ppm. 100 ppm is not itself a life safety hazard, but rather a lower threshold on the range of potentially very serious outcomes. It is unacceptable to reach these levels and combustion safety test and assurance procedures should have multiple safeguards to ensure this. Even if one thing goes terribly wrong or one very unlikely event occurs, these safeguards should ensure that these conditions will not occur.
2. Acute health hazard when concentrations reach levels exceeding health based standards for outdoor air. These are 9 ppm over 8 hours or 20 to 25 to 35 ppm over a 1 hour average. These levels are set for sensitive subpopulations. Outdoor air in many places in the United States has pollutant levels that exceed the analogous health based standards for PM_{2.5} and ozone. The goal should be that these standards are not exceeded other than under unusual or infrequent conditions. Having these conditions exceeded up to a few times per year is a tolerable - though, of course, still undesirable - failure rate. It would be unnecessarily cautious to spend a lot of money to make sure that these levels would never be reached.
3. Chronic health hazards resulting from frequent spillage that leads to pollutant levels in the home that comprise a substantial fraction of the chronic health standard level for NO₂ or are on the order of a few ppm averaged over days to weeks for CO. For NO₂, we are concerned about the “substantial fraction” because there are other sources of exposure including outdoor air. For CO, we are concerned about levels of a few ppm because there are plausible mechanisms and we don’t have adequate research. Also, because we should not have CO regularly being emitted into our homes at levels that produce a few ppm averaged over time.

Computer models can help extrapolate field measurements of parameters such as fan-induced depressurization Δp_f into anticipated long-term behavior, for example, the likelihood of backdrafting, and more importantly the consequent indoor air concentrations and exposures. Simulations may also help identify a progression of tests for successively evaluating the risks of backdrafting and vent stall. Such a progression would move from simple screening tests, to more accurate but potentially more difficult assessments of houses deemed at risk of significant indoor concentrations due to spillage from a combustion appliance.

This report begins to explore these possibilities, not in terms of what acceptable pollutant levels should be (which is a policy decision), but rather in terms of what appliance emissions can be tolerated and what concentrations can occur statistically. However, its conclusions are not

definitive, in part because the available models do not account for the thermal performance of the vent shaft, including the dynamics associated with heating the vent.

C7.1 Summary of Modeling Conclusions

On a more detailed level, the simulations performed here show the following:

- Conventional wisdom is correct in that, all else being equal, tightening the house envelope does increase the danger that an exhaust fan will cause backdrafting of a naturally-ventilated combustion appliance.
- For short (≤ 5 minutes) spillage events, the combustion safety protocols are protective against life threatening CO conditions, even in the case when the appliance is malfunctioning and has repeated intermittent spillage. However, the protocols likely establish CO thresholds that are too conservative for large homes with infrequent spillage events.
- Prolonged or continuous spillage events in a moderately airtight home could result in an acute hazard if the burner is malfunctioning. Therefore, combustion safety protocols should ensure that conditions of sustained spillage and high emissions do not exist without high ventilation.
- Reaching life threatening conditions in a moderately tight home with a natural draft appliance is rare and almost impossible for an induced draft appliance. However, in a very tight home ($a_{50} = 2 \text{ h}^{-1}$ or tighter), the combination of low air exchange rate and increased risk of spillage significantly increases the potential for prolonged pollutant exposure that could lead to a life-safety hazard. Therefore, we recommend that all combustion appliances be direct vent or installed outside the living space in very tight homes.
- Similar to CO, NO₂ from combustion spillage from natural draft and induced draft appliances may also present an acute hazard and should be included for combustion safety assurance. Because NO₂ concentrations from the appliance may be difficult to measure, we recommend instead measuring the total oxides of nitrogen (NO_x) and using an upper limit or a fraction of the NO_x that is characteristic to the appliance (i.e., about 10% or less of NO_x exhausted from storage water heaters is NO₂).
- The most dangerous conditions result from stalled flow in the appliance vent shaft. While strong negative (inward) airflows bring combustion products into the occupied space, they also dilute the combustion products. This is an important phenomenon that has not been recognized until now.
- Fan-induced pressure change - the metric used in current stress testing regimens - does not directly assess whether flow will stall or reverse in the vent shaft, because the pressure change needed to reverse flow in the vent shaft depends on weather conditions, which vary throughout the year.
- A large enough fan-induced pressure change does imply backdrafting. However, by the time fan-induced pressure change is large enough to guarantee backdrafting, it is almost

never of concern in terms of indoor air quality, due to the dilution that it contributes by outdoor air entering through the vent.

- Because the exhaust fan forces a minimum airflow through the occupied space, it (along with the generation rate for the combustion appliance) establishes an effective maximum concentration in the space (the fan-limited steady-state concentration).
- For the conservative model used here, the fan-limited steady-state concentration for a fairly small exhaust flow rate is in the neighborhood of the CPSC limit (25 ppmv). Increasing the exhaust flow only reduces the concentration ceiling established by the fan.
- Regardless of fan-induced depressurization, the building professional should always ensure that the appliance burner is clean, the appliance is functioning properly, the vent system is connected to the appliance, and draft is established in a short period of time.

These simulations probably are overly conservative, for a number of reasons:

- They do not account for combustion-related heating in the vent shaft, which will tend to encourage outward flow.
- The houses considered are small compared to the norm. Larger houses, for a fixed air change rate, allow more flow through adventitious leaks, and therefore (all else being equal) have a lower chance of backdrafting. Furthermore, larger houses provide a greater volume of air for diluting combustion products in the event backdrafting does occur.
- The assumed combustion appliance size has not been adjusted for the climate zone, and therefore may be large for many of the simulated houses. This gives a larger assumed generation rate than realistic, especially for warmer climate zones, which tend to have greater problems with backdrafting.
- The combustion appliance is assumed to operate, at best, at the outer limit of the acceptable range of generation rates.
- The combustion appliance is assumed to operate continuously, thus producing a greater mass of combustion product than realistic.

However, a number of modeling approximations mean the simulations may not always over-predict indoor concentrations:

- The well-mixed assumption under-estimates exposure for occupants close to a combustion source. Conversely, it can over-estimate exposure for thermally-stratified combustion products.
- Ignoring the relative timing of exhaust fan and appliance operation misses potential cross-correlation effects. For example, running an exhaust fan at the same time as a combustion appliance, and shutting it off when the appliance shuts off—as might be expected for a shower fan and water heater—would tend to increase the predicted long-

term average concentrations compared to those reported in the cyclic simulations of Section C4.

- The airflow driver and yearly distribution studies assume wind always creates suction at the vent cap, no matter what the wind direction. This tends to decrease the likelihood of backdrafting.

C7.2 Implications

The simulations, and the analytic results from the box model, focus attention on two aspects of the house-appliance system: (1) the combustion appliance is the best point of control of indoor air quality problems; and (2) the proper focus of a field test is not what happens when all the exhaust fans are operating at once, but rather what minimum exhaust fan flow is needed to just reverse flow in the vent shaft.

While backdrafting always should be avoided, it is not necessarily catastrophic. In cases where mechanical exhaust is strong enough to cause spillage, limiting the generation rate of the combustion appliance will always limit the concentration of combustion products in the occupied space. See, for example, Equation C26, which gives the fan-limited steady state concentration.

The critical exhaust fan flow rate is that which just reverses flow in the vent shaft. At zero vent shaft flow, combustion products enter the house, but dilution due to air brought in by the fan is at a minimum. Increasing the exhaust flow brings more outside air into the house (through both the vent shaft and the adventitious leaks), and therefore decreases the fan-limited steady state concentration. Therefore, the maximum exhaust fan flow rate, while it does give the highest likelihood of backdrafting, does not correspond to the worst consequences of backdrafting.

Simulations similar to those reported here could be used as part of a screening tool, either to help translate field measurements into a risk assessment, or to guide the field tests toward an appropriate level of testing. For example, Figure C5 suggests how pre-tabulated results could form the basis of a screening test that establishes, for a given house performance under a depressurization stress test, the maximum acceptable generation rate for a combustion appliance.

A more detailed test might attempt to force the flow in the appliance vent shaft to zero. Comparing the weather conditions at the time of the test, against the expected annual weather, would give an estimate of the worst-case exhaust flow (i.e., the smallest exhaust flow that could be expected to just stall a drafting vent shaft). If the exhaust fans in the house are able to establish that flow, then the test would proceed to a second stage. The worst-case exhaust flow, combined with an estimate of the effective mixing volume of the house, would imply a maximum “safe” source rate at which the combustion appliance could generate pollutants. Thus, if the exhaust flow needed to create zero vent shaft flow under worst-case weather conditions was very high, then the test protocol could account for dilution when establishing the critical performance of the appliance. Conversely, if only small mechanical exhaust was required to reverse flow in the vent shaft, the house would be deemed to have a higher risk, and further testing or mitigation would be needed.

The feasibility of such an approach hinges on: (1) the ability to easily and reliably find the cutoff exhaust flow at which the vent shaft stops drawing; and (2) whether, from a statistical view, such a test imposes an overly conservative limit on the combustion source rate. This study cannot, of course, speak to the first question. However, we note that the simulations shown in Figure C13 assume a small house relative to most California homes, a large combustion appliance relative to the size of the house, a source rate at the edge of the ANSI limit, and a not unreasonably large exhaust fan. These assumptions, perhaps not coincidentally, lead to worst-case concentration estimates very near the CPSC limits. This suggests that an appropriately sized and well-tuned appliance should be able to pass a test that seeks to limit the CO source rate based on the house's worst-case ventilation characteristics.

C7.3 Model Improvements Needed

Before simulations can be used to guide testing, or to safely assess the risks associated with a particular house, the models would have to be improved. As noted above, the greatest limitation of the simulation studies performed here is the lack of a coupled airflow-thermal model. The model does not account for the temperature of air in the vent shaft, which due to convection heat transfer at the shaft surface, depends on the airflow rate. A useful model must include these and other thermal effects, such as convective and radiative heat losses in the attic. Unfortunately, our current tools do not incorporate the required physics, or do not represent them adequately.

Furthermore, a coupled airflow-thermal simulation tool would have to account for the dynamics associated with heating in the vent shaft over the course of an entire year. For example, even if an operating appliance can maintain draft when an exhaust fan turns on, it may not be able to establish draft if the fan already was running when the appliance begins to heat up. That is, the sequence of events matters.

In principle, a simulation tool could assume that the vent shaft was able to establish draft, then use steady-state thermal and airflow models to find consistent flows and temperatures under that assumption. The results might correspond to the case that an operating combustion appliance already had established draft at the time the exhaust fan turned on. Such a steady-state analysis should be able to detect most cases where the exhaust fan was able to “pinch off” a drafting vent shaft (since the search for a consistent airflow-thermal solution would drive the estimated vent shaft flow to zero, and hence would drive the estimated vent shaft air temperature towards some average of the room and outside temperatures).

Other model improvements do lie within the capabilities of CONTAM. These include: refining the treatment of wind at the vent cap; scheduling the combustion appliance; and scheduling the exhaust fan. To be conservative, a model could simply make the exhaust fan turn on when the combustion appliance is on, and off when the appliance is off. This would partially relieve the need to choose absolute times at which the source turns on and off, since the relative schedule (intermittency and duration) matters most. However, interactions between the fan and appliance schedules, and the weather, still would have to be taken into account.

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APPENDIX D:

Box Model - Exposure to Intermittent Sources

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This appendix shows details behind some of the box model results presented in Section C3 of Appendix C.

Consider a source that turns on at time $t = 0$, runs at a constant mass rate s until $t = t_n$, and then turns off. We seek the total exposure over the longer interval from $t = 0$ to $t = T$, where $T > t_n$.

Suppose $a > 0$, $k \geq 0$, and $C_o \geq 0$ are fixed. Note this implies $\lambda > 0$ is constant as well. Then the total exposure consists of the exposure from $t = 0$ to t_n , plus that from t_n to T . From Equation C9:

$$\begin{aligned} E_{0:T} &= \frac{1}{\lambda} (\sigma_s t_n + C\{0\} - C\{t_n\}) + \frac{1}{\lambda} (\sigma_n (T - t_n) + C\{t_n\} - C\{T\}) \\ &= \frac{1}{\lambda} (\sigma_s t_n + \sigma_n (T - t_n) + C\{0\} - C\{T\}) \end{aligned} \quad (D1)$$

where σ_s holds for $0 \leq t \leq t_n$; and σ_n holds after the source turns off. Note that $\sigma_s > 0$, while $\sigma_n \geq 0$ (for example, zero outdoor concentration makes $\sigma_n = 0$).

Since the indoor source is off after $t = t_n$:

$$\begin{aligned} \sigma_s t_n + \sigma_n (T - t_n) &= \frac{s}{V} t_n + aPC_o t_n + aPC_o (T - t_n) \\ &= aPC_o T + \frac{s}{V} t_n \end{aligned}$$

Furthermore Equation C8 gives:

$$\begin{aligned} C\{T\} &= \frac{\sigma_n}{\lambda} + \left(C\{t_n\} - \frac{\sigma_n}{\lambda} \right) e^{-\lambda(T-t_n)} \\ &= \frac{\sigma_n}{\lambda} + \left(\frac{\sigma_s}{\lambda} + \left[C\{0\} - \frac{\sigma_s}{\lambda} \right] e^{-\lambda t_n} - \frac{\sigma_n}{\lambda} \right) e^{-\lambda(T-t_n)} \\ &= \frac{\sigma_n}{\lambda} + \left(\frac{s}{\lambda V} + \left[C\{0\} - \frac{\sigma_s}{\lambda} \right] e^{-\lambda t_n} \right) e^{-\lambda(T-t_n)} \end{aligned}$$

where the last line follows since $\sigma_s - \sigma_n = s/V$. Combining:

$$\lambda E_{0:T} = aPC_oT + \frac{s}{V}t_n + C\{0\} - \frac{\sigma_n}{\lambda} - \left(\frac{s}{\lambda V} + \left[C\{0\} - \frac{\sigma_s}{\lambda} \right] e^{-\lambda t_n} \right) e^{-\lambda(T-t_n)} \quad (D2)$$

Now assume the initial indoor concentration, $C\{0\}$, is at equilibrium with that outdoors, C_o . In practice, this might mean that no indoor source has operated for 4 to 5 time constants $1/\lambda$ prior to $t = 0$. Then from Equation C7:

$$C\{0\} = \frac{\sigma_n}{\lambda} \quad (D3)$$

and the exposure over $0 \leq t \leq T$ becomes:

$$E_{0:T} = \frac{aPC_oT}{\lambda} + \frac{st_n}{\lambda V} - \frac{s}{\lambda^2 V} (e^{\lambda t_n} - 1) e^{-\lambda T} \quad (D4)$$